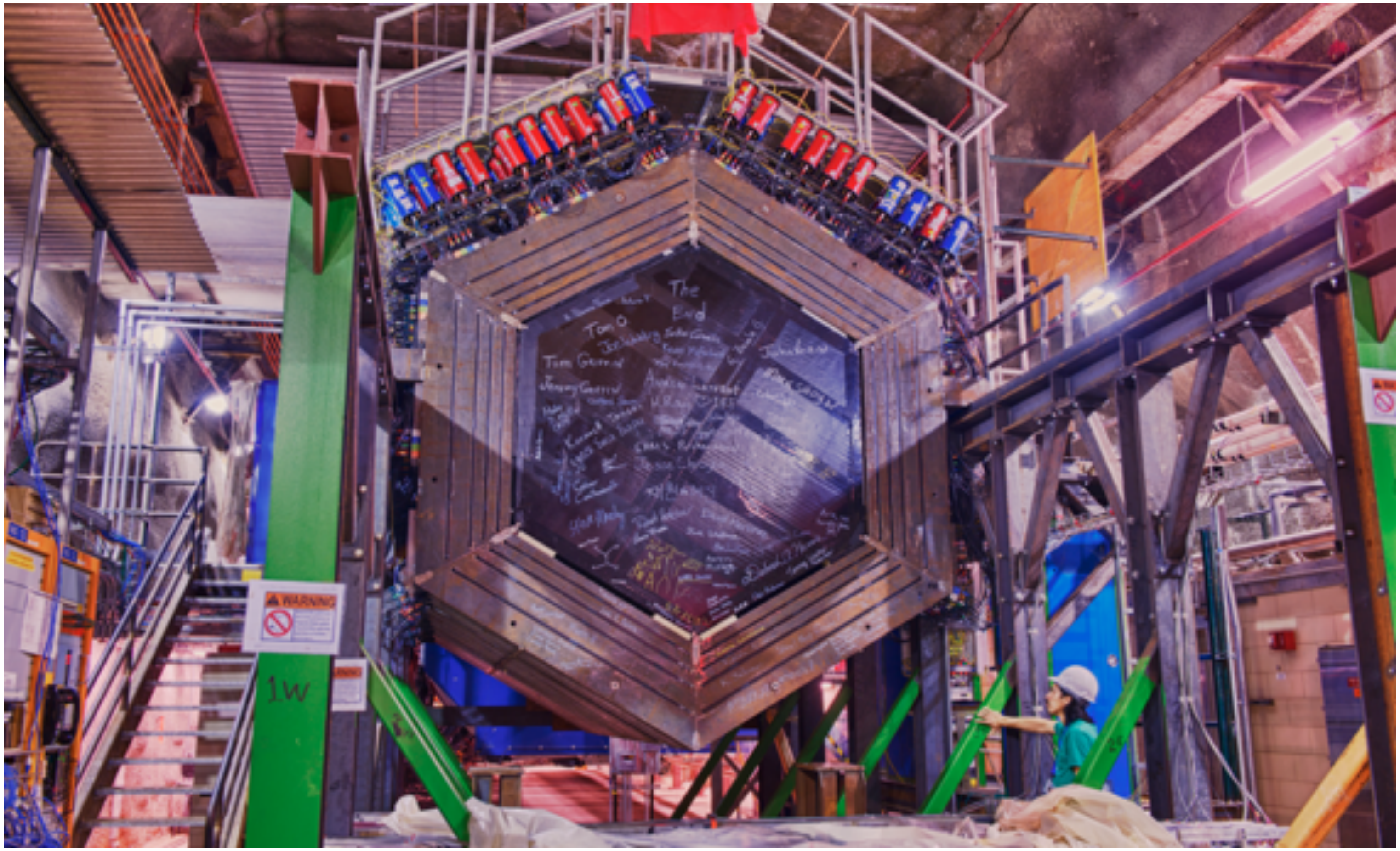


MINERvA Analysis and Statistical Methods

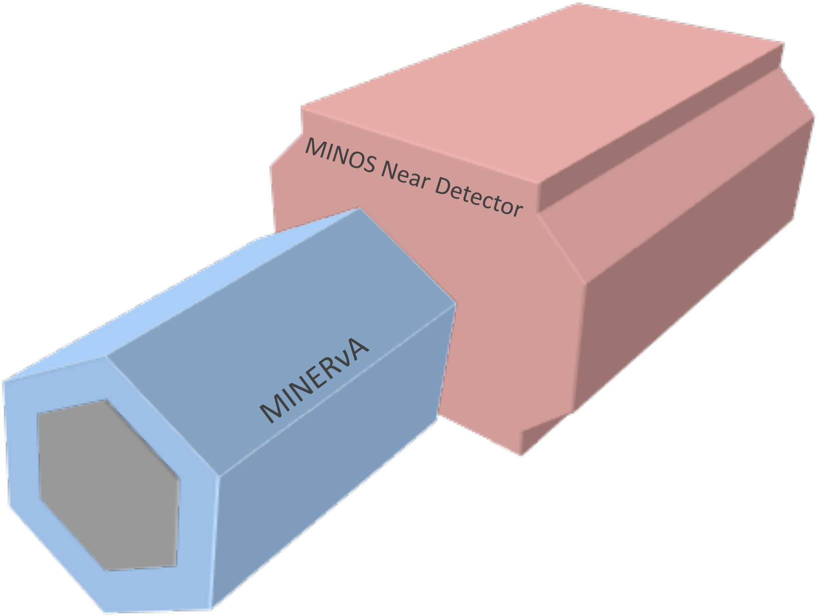
Laura Fields

Outline

- MINERvA
  - What
  - How
- Statistical problems and how we've solved them:
  - Propagating systematic uncertainties
  - Constraining the NuMI flux
  - Unfolding

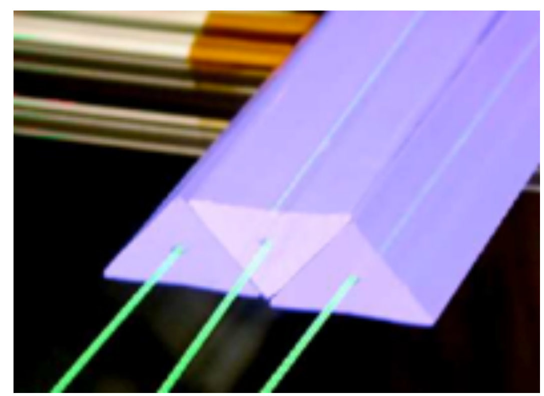
Introduction: What

- A neutrino detector in the NuMI beam at Fermilab designed to study **ν_μ and ν_e** interactions with nuclei (and to compare across different nuclei)



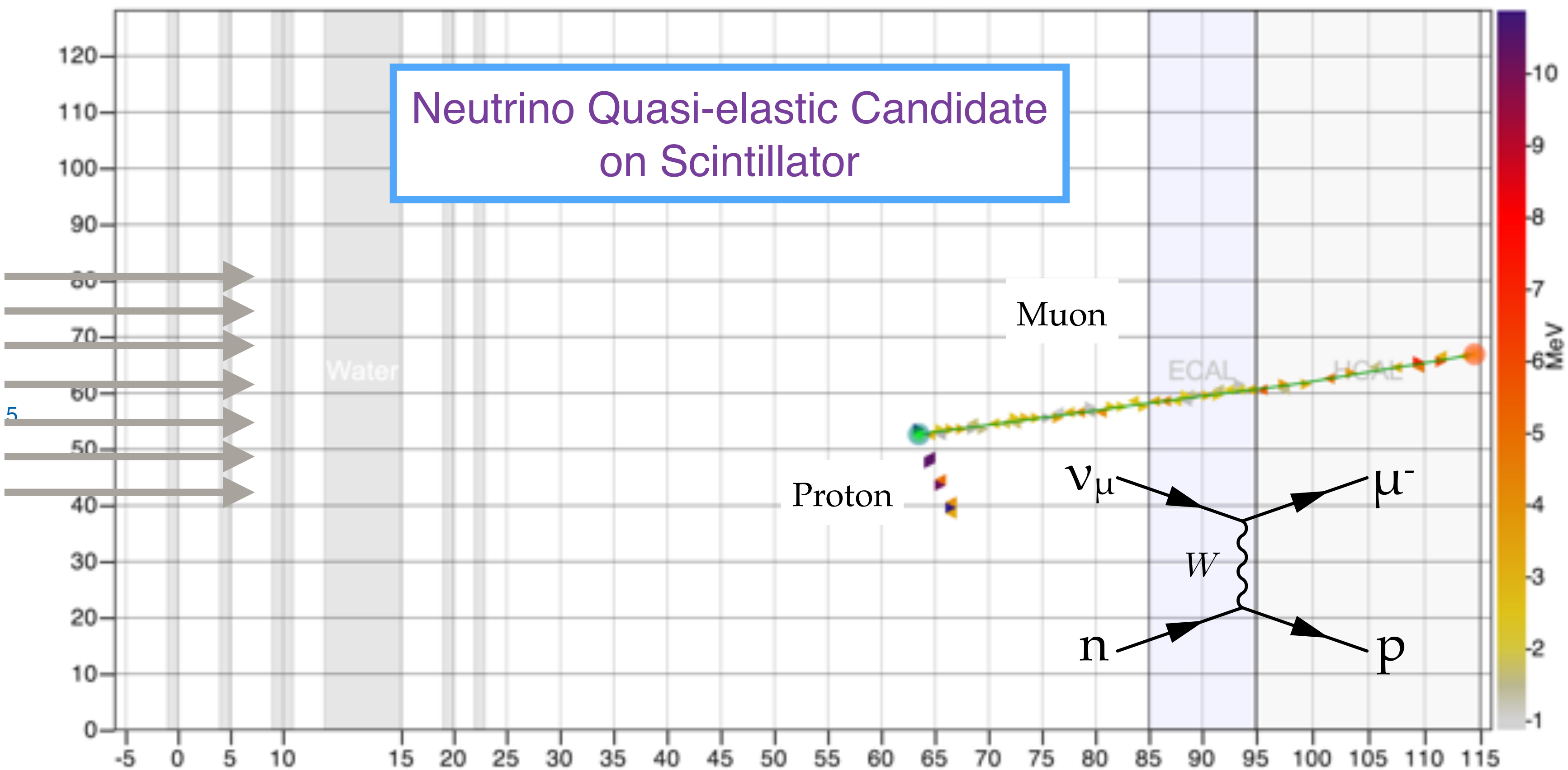
Introduction: What

- Made of > 30,000 strips of plastic scintillator interspersed with other materials
- Scintillator creates light when charged particles move through it



Introduction: What

A sample neutrino interaction in MINERvA:



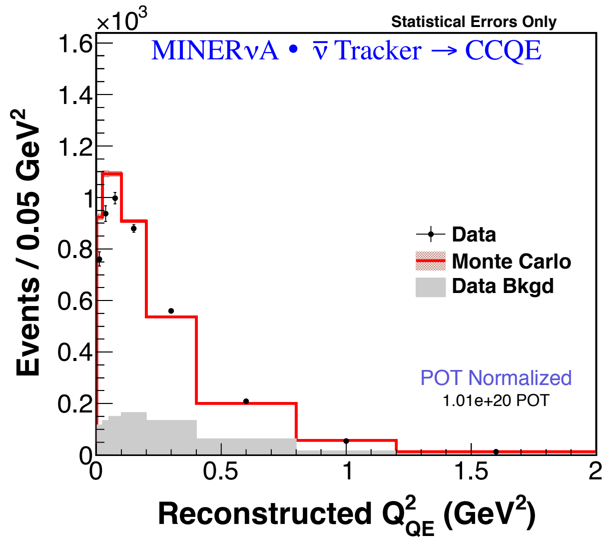
Introduction: What

- MINERvA measures cross sections — probabilities that some processes will happen
- Often we measure differential cross sections with respect to some variable
- For example, for our first measurement, we measured quasi-elastics (the example on the previous slide) as a function of a variable called Q^2.
- Here is the basic recipe for a cross section:

$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i \left(\Phi T\right) \Delta Q^2_{\mathrm{QE},i}}$$

Introduction: How

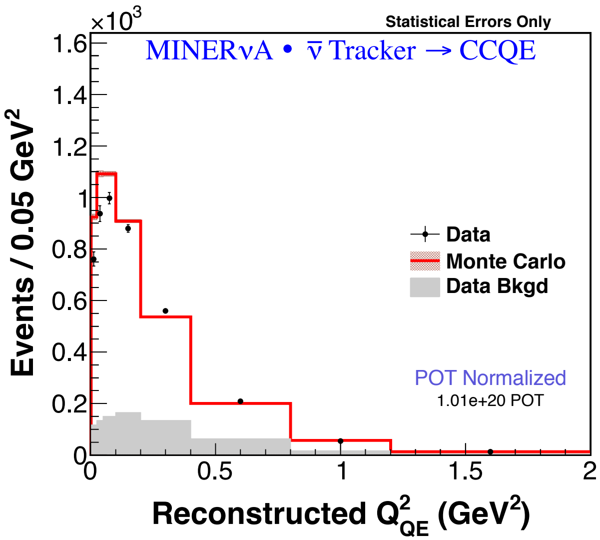
- We start by a selecting a sample of events enriched with whatever process we want to measure and bin them in the variable we want to measure

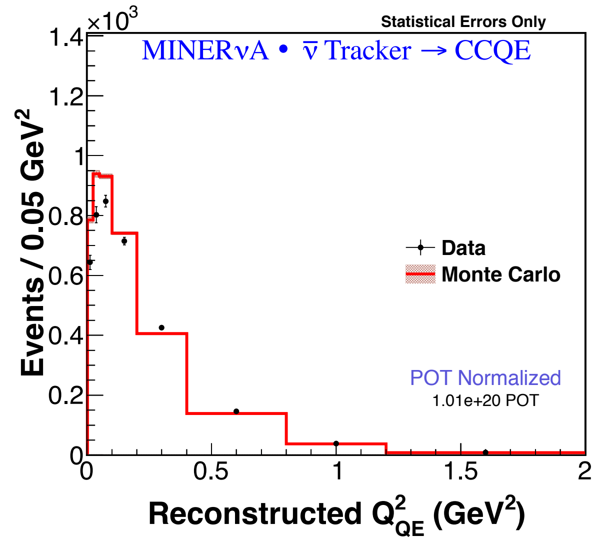


$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i\,(\Phi T)\,\Delta Q^2_{\mathrm{QE},i}}$$

Introduction: How

- We then subtract our best estimate of backgrounds (almost always constrained with a data fit or sideband)

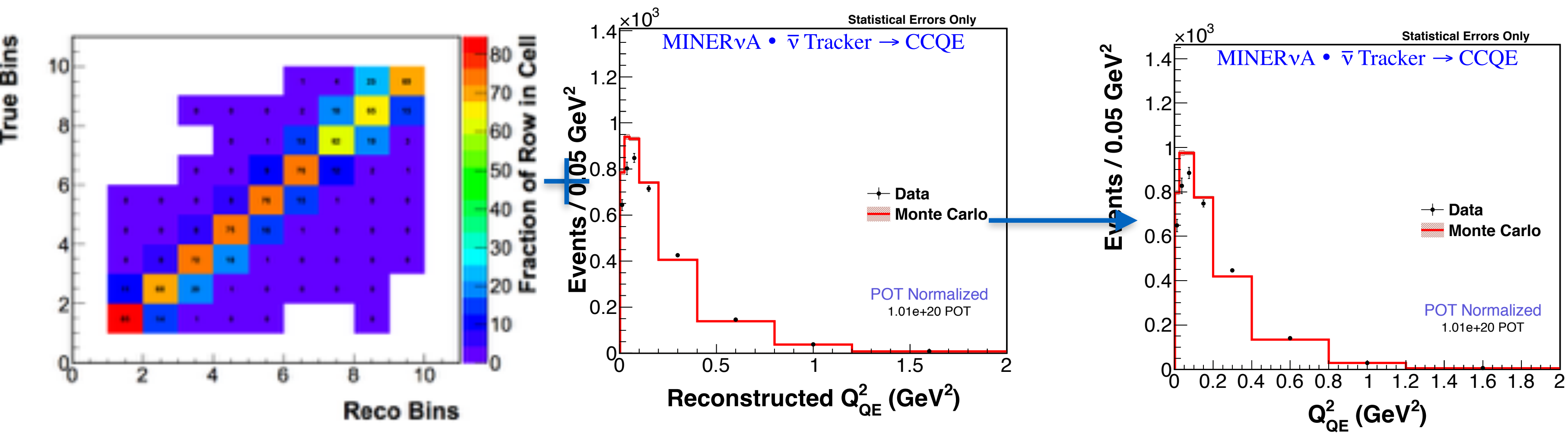




$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i\left(\Phi T\right)\Delta Q^2_{\mathrm{QE},i}}$$

Introduction: How

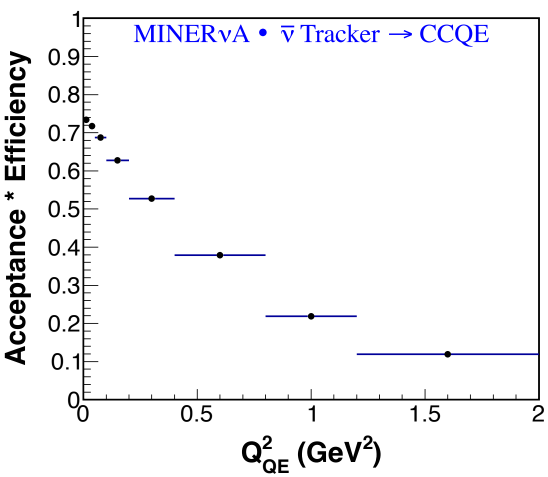
- We unfold to correct for detector smearing in the variable we are measuring (more on this shortly):



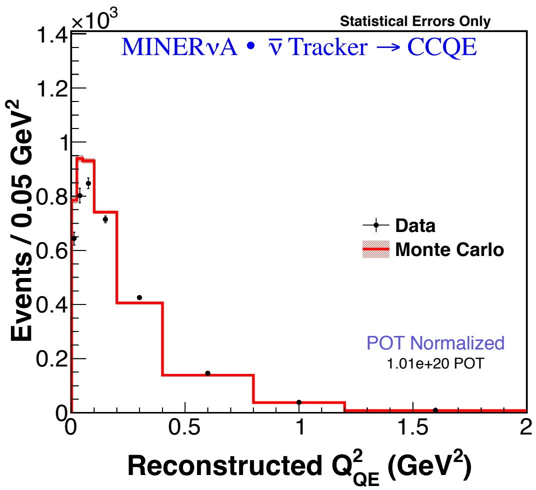
$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i \left(\Phi T\right) \Delta Q^2_{\mathrm{QE},i}}$$

Introduction: How

- We then correct for analysis efficiency (events lost due to our analysis cuts) and detector acceptance (events lost due to detector geometry):



X



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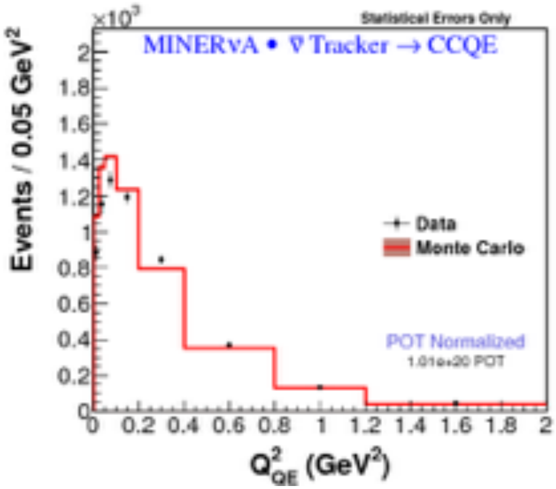
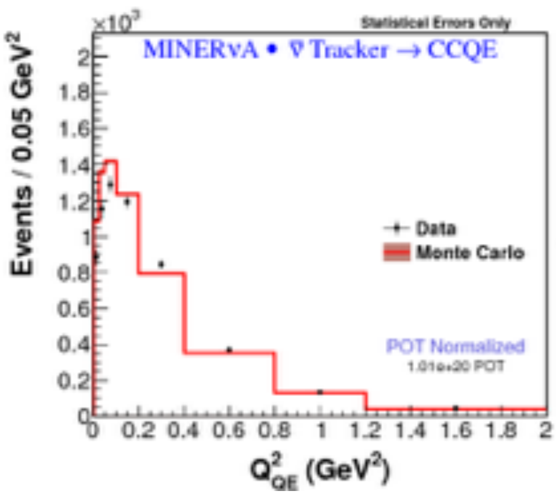
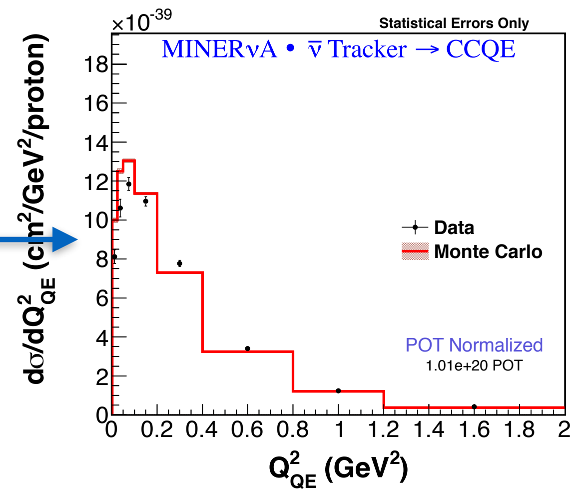


$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i \left(\Phi T\right) \Delta Q^2_{\mathrm{QE},i}}$$

Introduction: How

- Finally, we divide by the number of targets (usually nucleons) in our detector and the number of neutrinos in our beam (more on this soon):

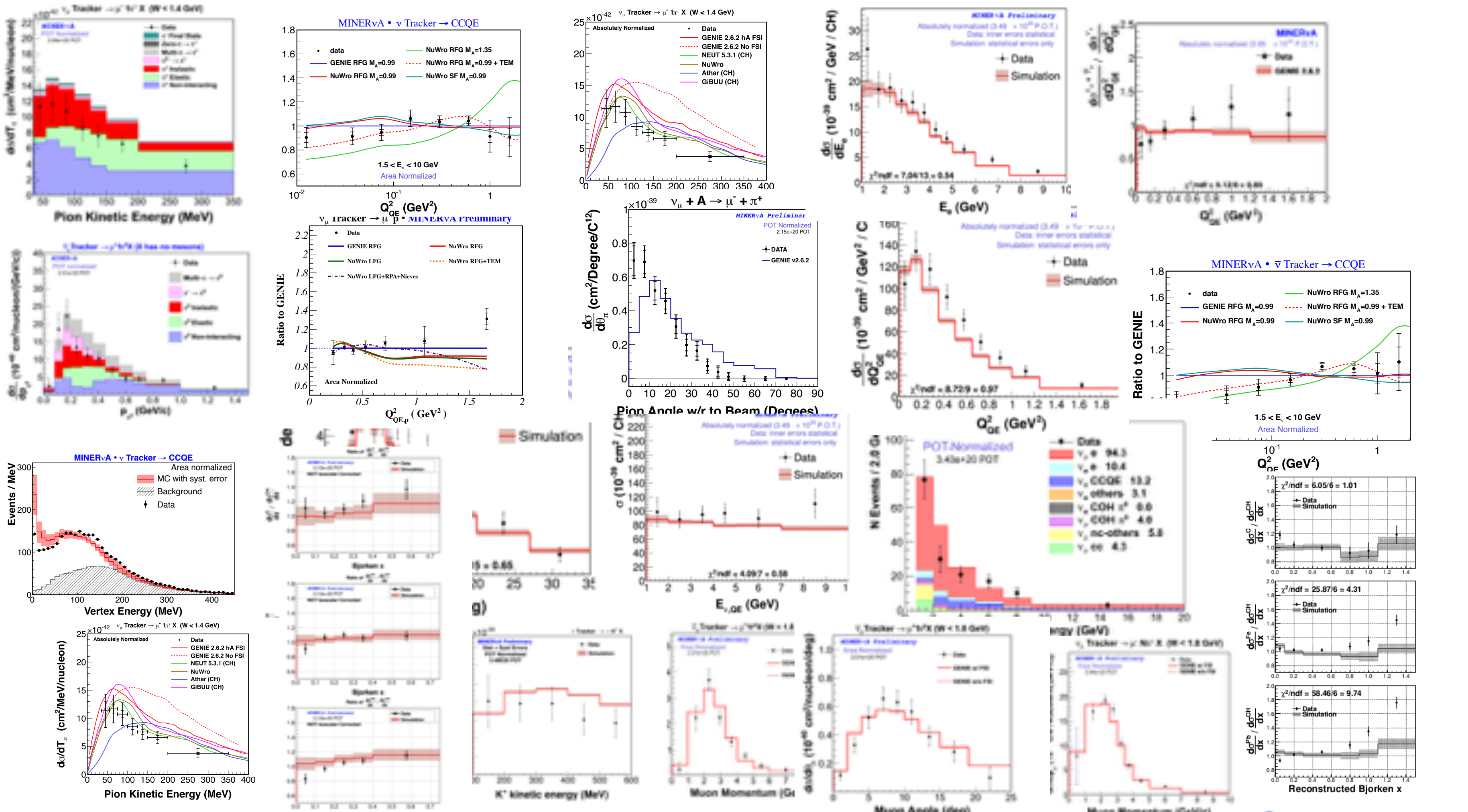




$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i \left(\Phi T\right) \Delta Q^2_{\mathrm{QE},i}}$$

Introduction: How

- And then we do that, over and over and over again

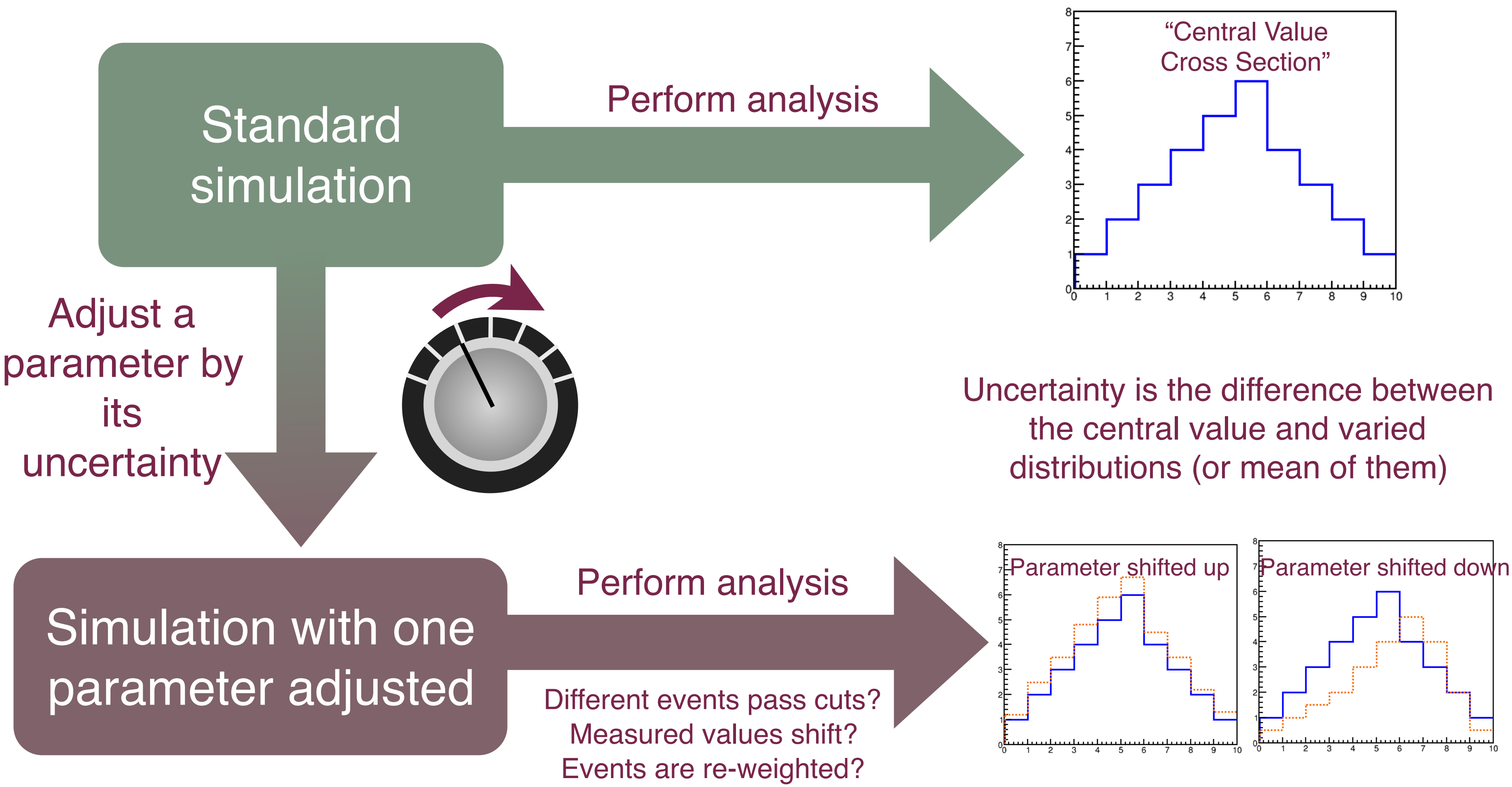


Propagating Systematic Uncertainties

- As everyone in this room definitely knows, a cross section measurement is meaningless without an error bar (and correlation matrix!)
- MINERvA cross section measurements have systematic uncertainties from many sources, e.g.
  - Neutrino flux
  - Mass of detector
  - Energy scales of reconstructed particles/energy
  - Tracking efficiencies
  - Models of neutrino interactions and FSI
  - Deadtime

Propagating Systematic Uncertainties

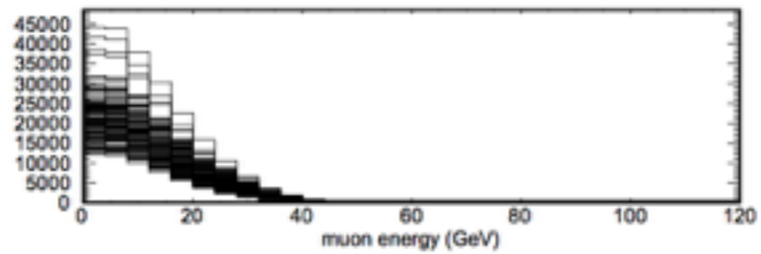
- We assess systematic uncertainties in the usual way:



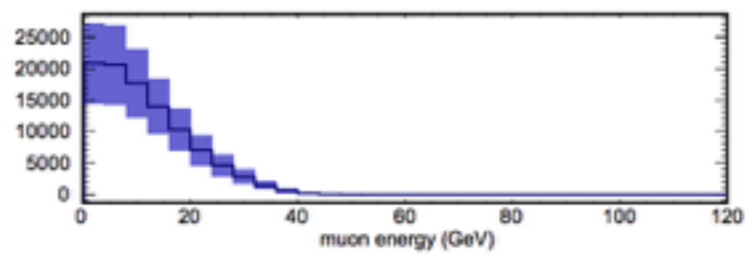
Propagating Systematic Uncertainties

- When assessing systematic uncertainties due to many correlated parameters, we use the "many-universe technique"
  - Uncertain parameters are selected randomly from their probability distributions
  - This is done many times (100-1000)

For each set of parameters (ie in each "universe"), a new simulated distribution is produced corresponding to that universe



The RMS of of the predicted distribution in a particular bin becomes the uncertainty on that bin



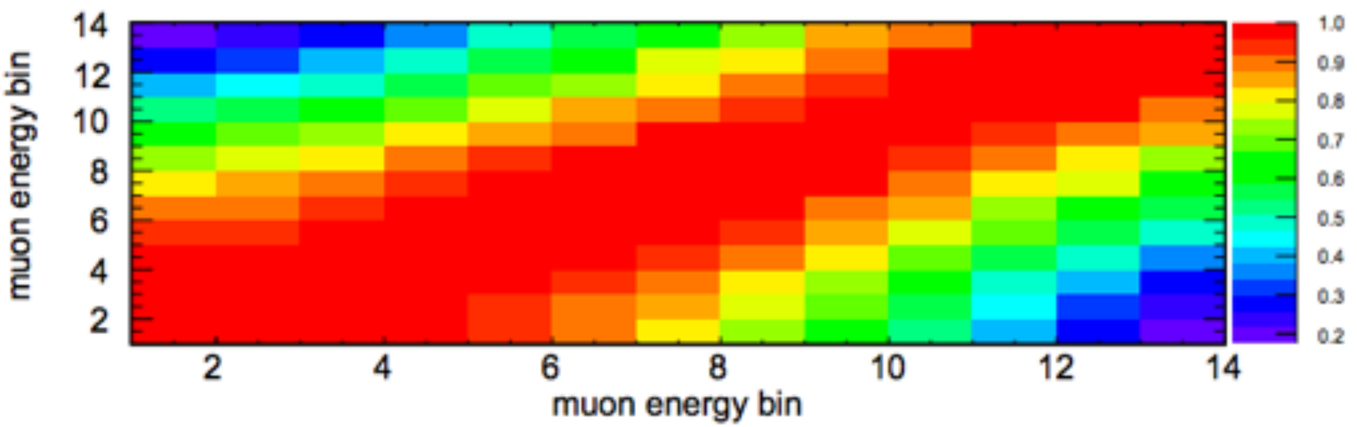
Propagating Systematic Uncertainties

- Correlations are also extracted from the universes

cross section in bin k of ith universe

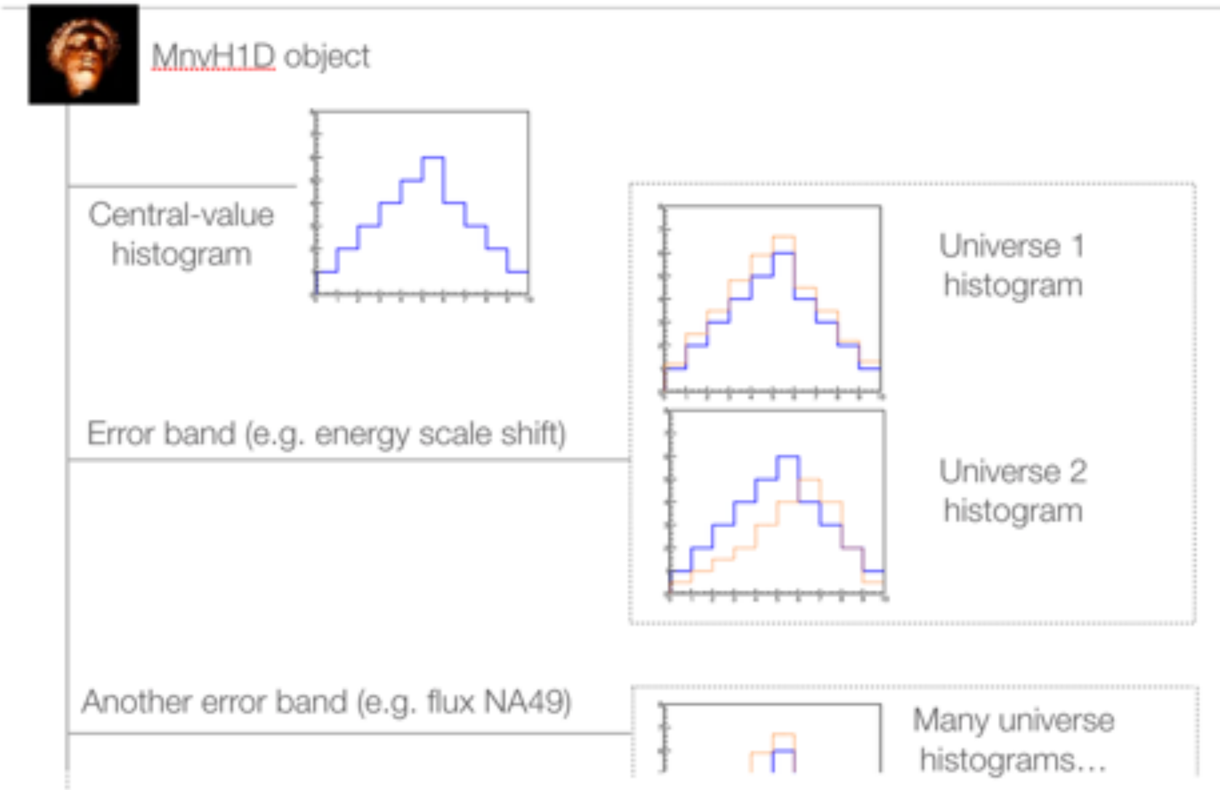
$$\mathrm{cov}(j,k) = \frac{1}{N}\sum_{i}^{\mathrm{histos}}(\nu_j - n_{ij})(\nu_k - n_{ik})$$

cross section in bin j of central value



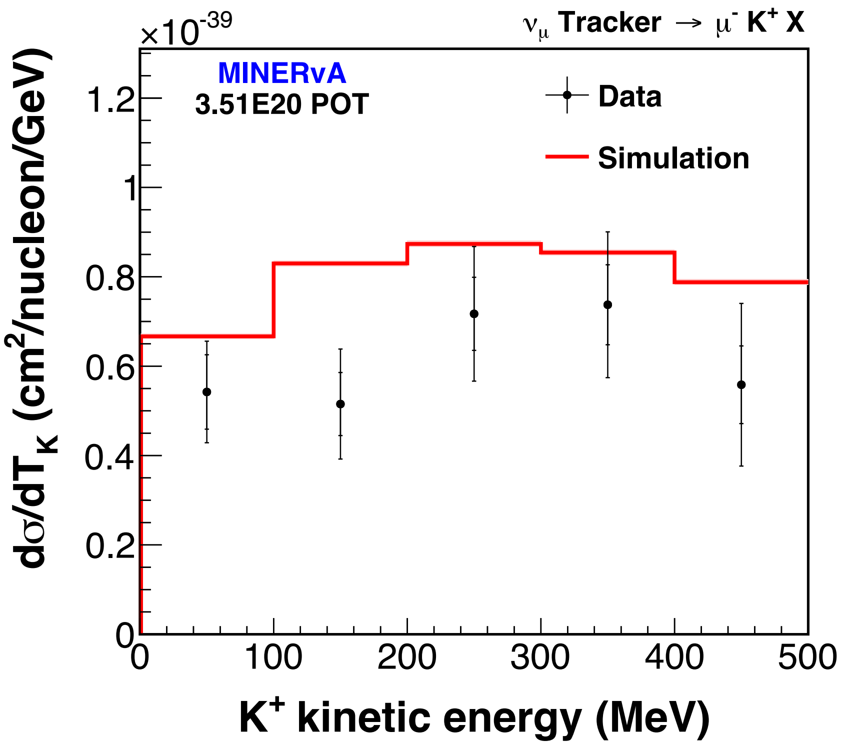
Propagating Systematic Uncertainties

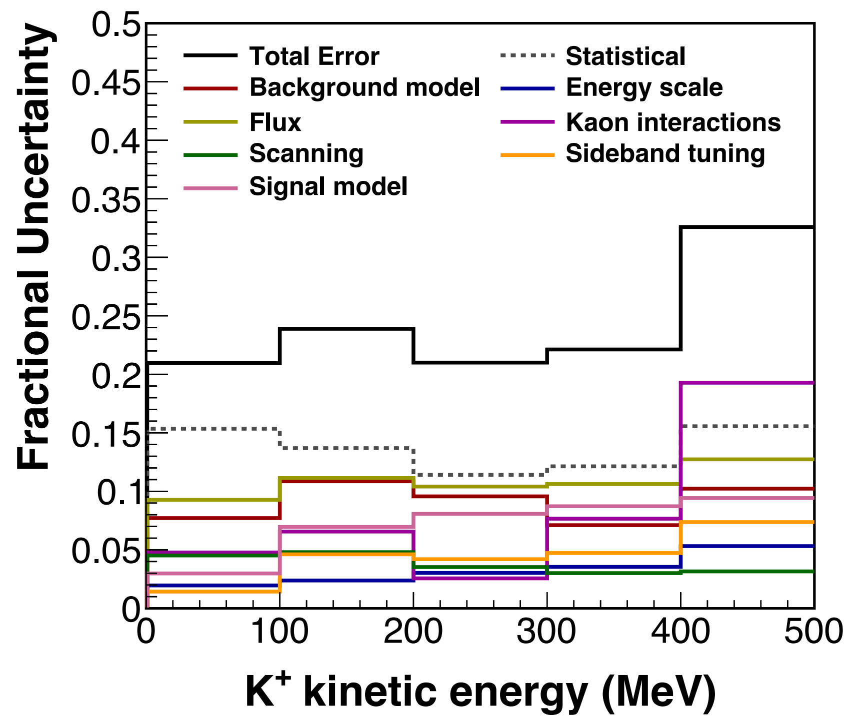
- The multi-universe method is so critical to MINERvA's analysis methods that we have created extensions of ROOT histogram object to facilitate it:



Propagating Systematic Uncertainties

- The MnvH1D (and MnvH2D) class makes computing and plotting systematic uncertainties straightforward

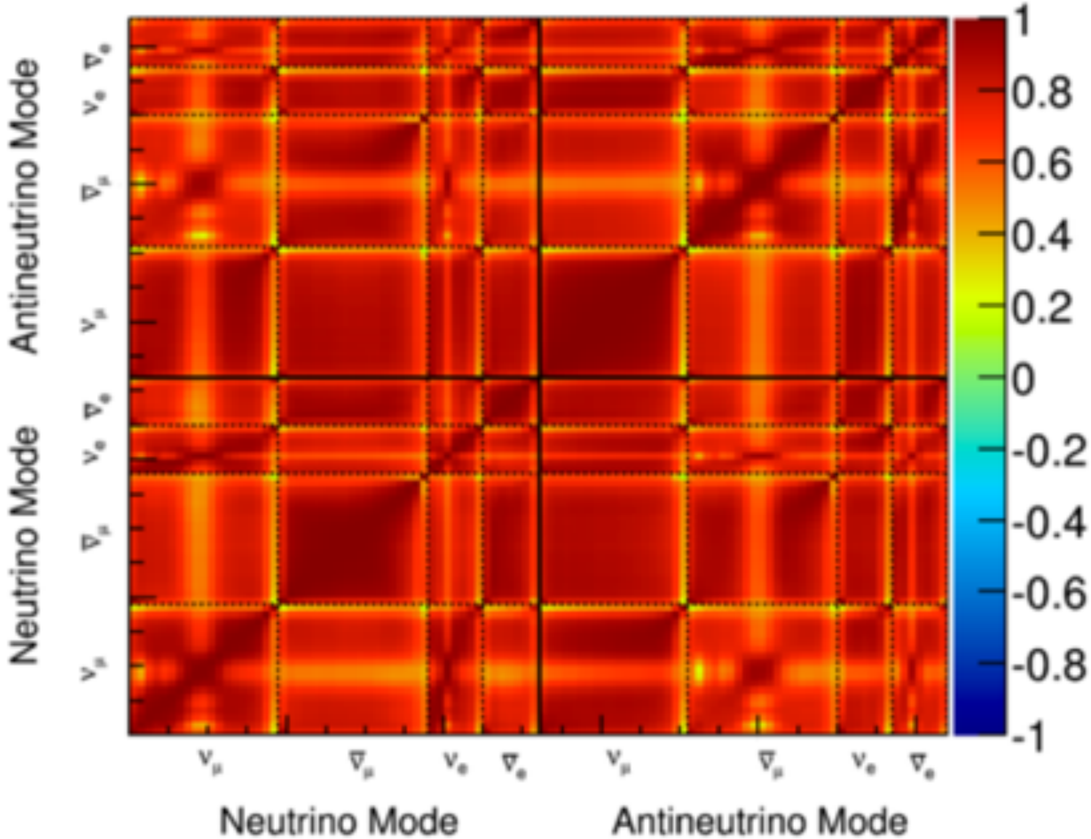




Phys. Rev. D 94, 012002 (2016)

Propagating Systematic Uncertainties

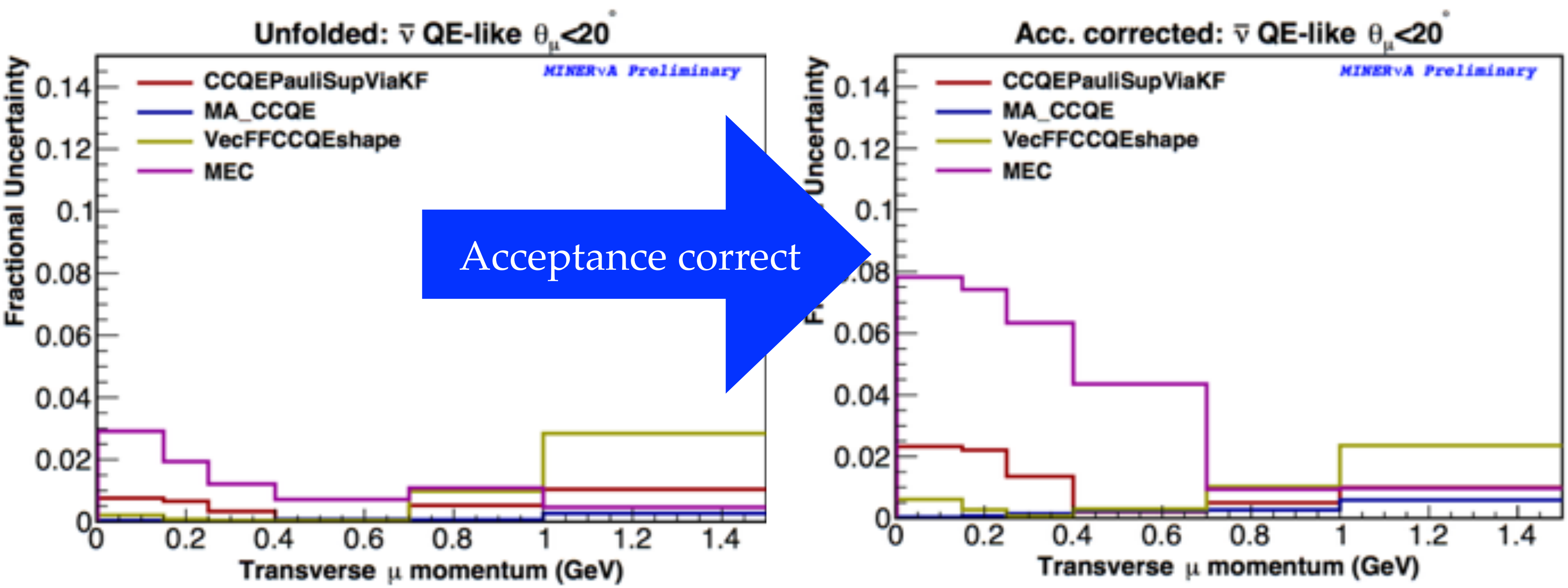
- As well as correlations:



Covariance matrix of flux in neutrino energy bins requested by DUNE that was easy since we had flux MnvH1D's available

Propagating Systematic Uncertainties

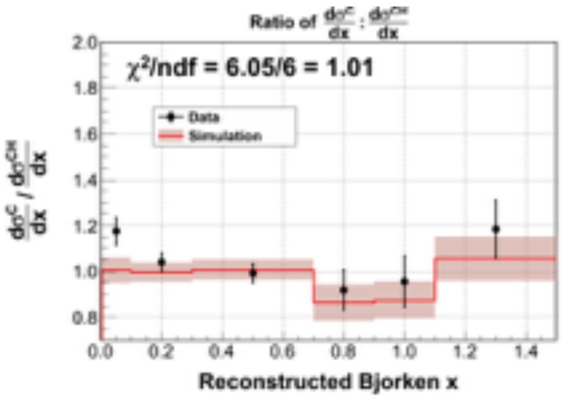
- MnvH1D construction starts at the beginning of the analysis, and is propagated through background subtraction, efficiency correction, etc. This is extremely useful for understanding where systematics become a problem:



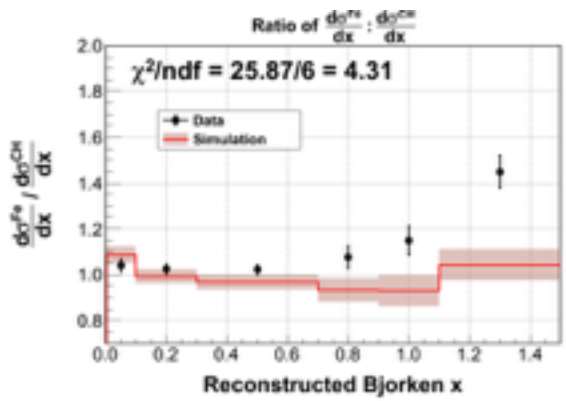
C. Patrick FNAL W&C Seminar, 17 June 2016

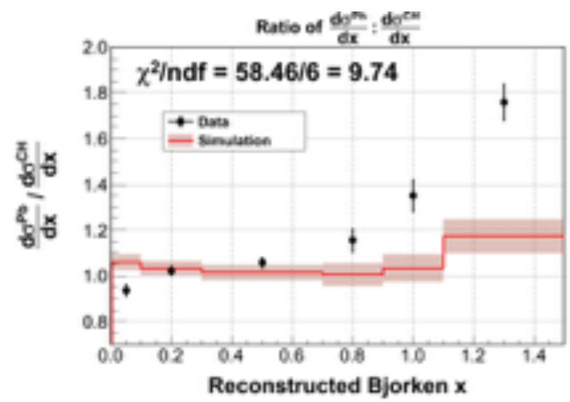
Propagating Systematic Uncertainties

- It also makes taking ratios of measurements with correlated uncertainties extremely straightforward (ratios are calculated universe-by-universe):



charged-current inclusive cross section ratios of different nuclei to scintillator

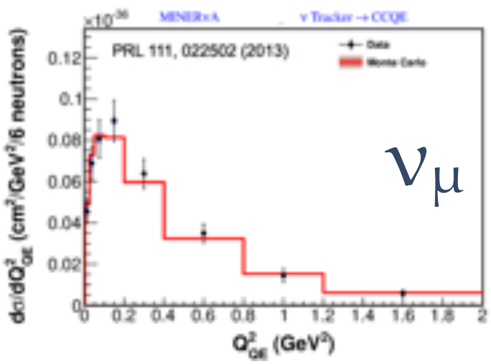


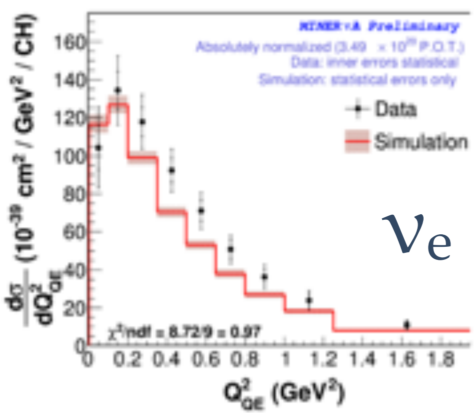


Phys. Rev. Lett. 112, 231801 (2014)

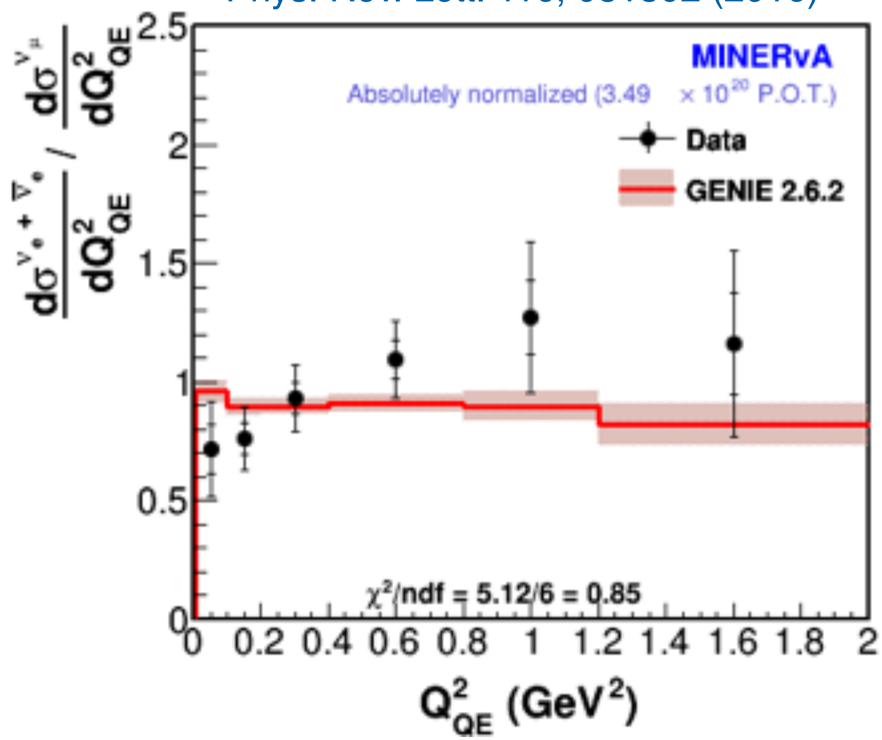
Propagating Systematic Uncertainties

- It also makes taking ratios of measurements with correlated uncertainties extremely straightforward (ratios are calculated universe-by-universe):



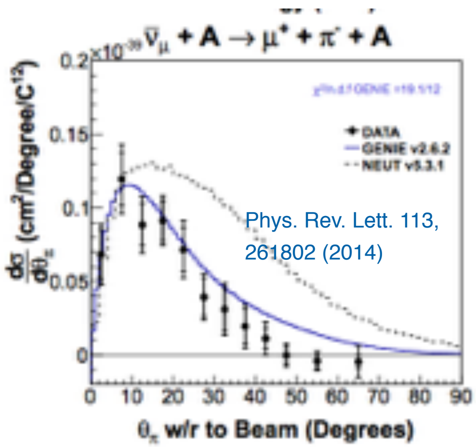


Phys. Rev. Lett. 116, 081802 (2016)



Propagating Systematic Uncertainties

- We have typically provided our results to the world in the form of cross section values, errors and correlations matrix:



Phys. Rev. Lett. 113, 261802 (2014)

Degrees	0 - 5	5 - 10	10 -15	15 - 20	20 - 25	25 - 30	30 - 35	35 - 40	40 - 45	45 - 50	50 - 60	60 - 70
0 - 5	0.0552	0.0801	0.0547	0.0661	0.0640	0.0369	0.0322	0.0227	0.0184	0.0014	-0.0006	0.0042
5 - 10	0.0801	0.1166	0.0797	0.0961	0.0932	0.0540	0.0470	0.0333	0.0269	0.0022	-0.0008	0.0061
10 -15	0.0547	0.0797	0.0547	0.0659	0.0641	0.0370	0.0323	0.0229	0.0187	0.0016	-0.0004	0.0043
15 - 20	0.0661	0.0961	0.0659	0.0796	0.0774	0.0446	0.0390	0.0277	0.0226	0.0019	-0.0005	0.0052
20 - 25	0.0640	0.0932	0.0641	0.0774	0.0760	0.0438	0.0385	0.0276	0.0228	0.0022	-0.0003	0.0052
25 - 30	0.0369	0.0540	0.0370	0.0446	0.0438	0.0255	0.0223	0.0160	0.0132	0.0013	-0.0001	0.0030
30 - 35	0.0322	0.0470	0.0323	0.0390	0.0385	0.0223	0.0196	0.0141	0.0117	0.0012	-0.0001	0.0027
35 - 40	0.0227	0.0333	0.0229	0.0277	0.0276	0.0160	0.0141	0.0102	0.0086	0.0010	0.0000	0.0019
40 - 45	0.0184	0.0269	0.0187	0.0226	0.0228	0.0132	0.0117	0.0086	0.0074	0.0009	0.0002	0.0017
45 - 50	0.0014	0.0022	0.0016	0.0019	0.0022	0.0013	0.0012	0.0010	0.0009	0.0002	0.0001	0.0002
50 - 60	-0.0006	-0.0008	-0.0004	-0.0005	-0.0003	-0.0001	-0.0001	0.0000	0.0002	0.0001	0.0001	0.0001
60 - 70	0.0042	0.0061	0.0043	0.0052	0.0052	0.0030	0.0027	0.0019	0.0017	0.0002	0.0001	0.0004

TABLE XVII: Anti-neutrino $d\sigma/d\theta_\pi$ flux systematic covariance matrix $\times 10^{-81}$

But given their utility, we are considering eventually making the MnvH1D's public

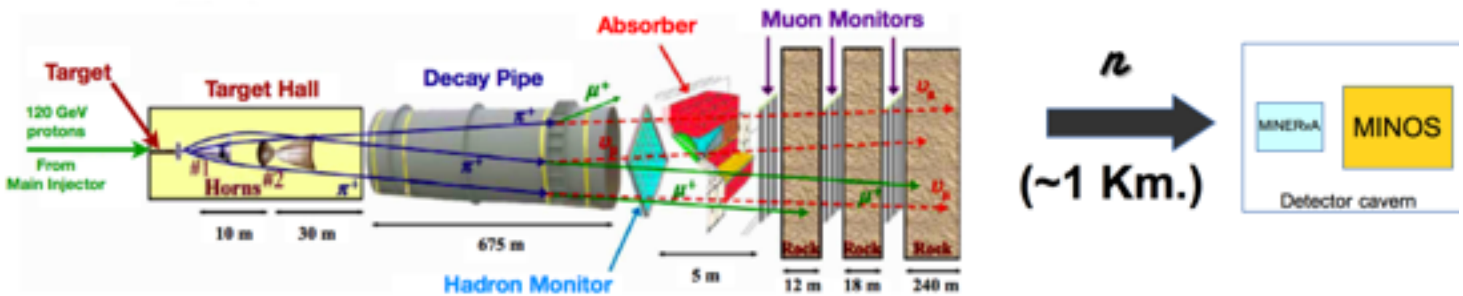
Degrees	0 - 5	5 - 10	10 -15	15 - 20	20 - 25	25 - 30	30 - 35	35 - 40	40 - 45	45 - 50	50 - 60	60 - 70
0 - 5	0.0931	0.0923	0.0859	0.0256	0.0682	0.0426	0.0683	0.0556	0.0543	0.0173	0.0259	0.0859
5 - 10	0.0923	0.1068	0.0968	0.0311	0.0804	0.0525	0.0815	0.0675	0.0671	0.0246	0.0319	0.0988
10 -15	0.0859	0.0968	0.1070	0.0336	0.0804	0.0567	0.0837	0.0692	0.0696	0.0300	0.0353	0.0917
15 - 20	0.0256	0.0311	0.0336	0.0280	0.0347	0.0295	0.0354	0.0330	0.0334	0.0220	0.0182	0.0305
20 - 25	0.0682	0.0804	0.0804	0.0347	0.0848	0.0550	0.0756	0.0663	0.0659	0.0331	0.0341	0.0807
25 - 30	0.0426	0.0525	0.0567	0.0295	0.0550	0.0545	0.0566	0.0514	0.0519	0.0313	0.0280	0.0524
30 - 35	0.0683	0.0815	0.0837	0.0354	0.0756	0.0566	0.0856	0.0678	0.0682	0.0349	0.0352	0.0803
35 - 40	0.0556	0.0675	0.0692	0.0330	0.0663	0.0514	0.0678	0.0690	0.0612	0.0339	0.0321	0.0674
40 - 45	0.0543	0.0671	0.0696	0.0334	0.0659	0.0519	0.0682	0.0612	0.0693	0.0349	0.0326	0.0664
45 - 50	0.0173	0.0246	0.0300	0.0220	0.0331	0.0313	0.0349	0.0339	0.0349	0.0310	0.0197	0.0248
50 - 60	0.0259	0.0319	0.0353	0.0182	0.0341	0.0280	0.0352	0.0321	0.0326	0.0197	0.0216	0.0321
60 - 70	0.0859	0.0988	0.0917	0.0305	0.0807	0.0524	0.0803	0.0674	0.0664	0.0248	0.0321	0.1003

TABLE XVIII: Anti-neutrino $d\sigma/d\theta_\pi$ non-flux systematic covariance matrix $\times 10^{-81}$

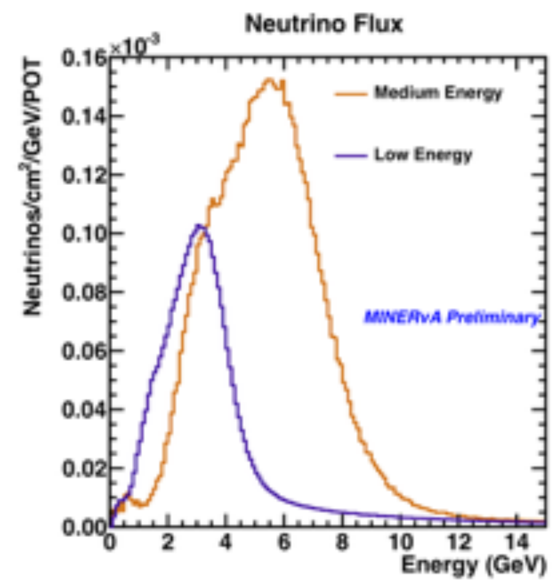
Constraining the NuMI Flux

Constraining the NuMI Flux

- One of our most important systematic uncertainties: the neutrino flux



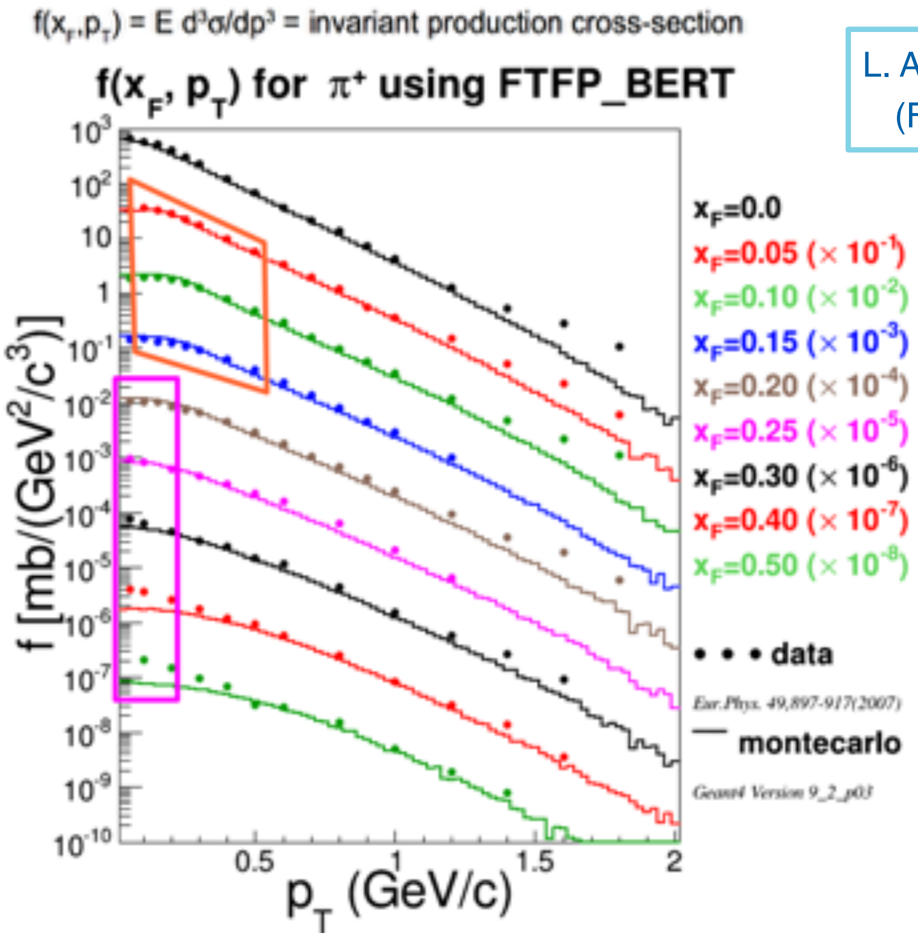
$$\sigma = \frac{N}{\epsilon A \Phi}$$



- Flux integral is in the denominator of all of our cross section; also is the starting point of simulations used to estimated backgrounds, acceptance and smearing
- Flux simulation starts with a GEANT4 simulation of the NuMI beam line (G4NuMI)

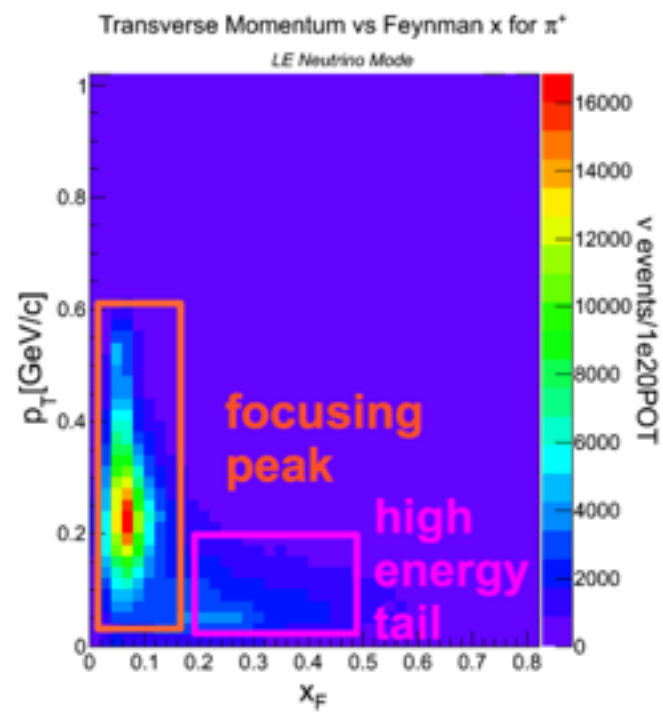
Constraining the NuMI Flux

- One problem: Geant4 does not always agree with external data:



L. Aliaga PhD thesis
(FNAL-2016-03)

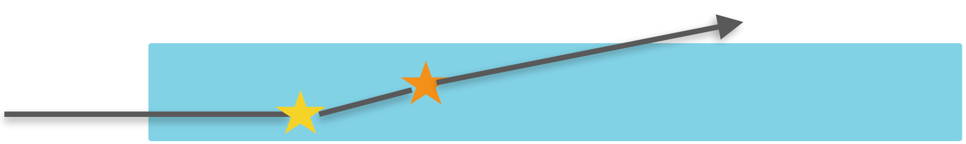
$$x_F = 2\frac{P_L}{E_{cm}}$$



Constraining the NuMI Flux

- We force the simulation to match external data
- How this works in practice:
  - Complete information about cascades leading to a neutrino is recorded for each proton on target and stored in the flux tuple
  - Including interaction materials and ancestor kinematics
  - In MINERvA analyses, neutrino events are weighted by:

$$w_{\mathrm{HP}} = \frac{f_{\mathrm{Data}}\left(x_F, p_T, E\right)}{f_{\mathrm{MC}}\left(x_f, p_T, E\right)} \qquad f = E\frac{d^3\sigma}{dp^3}$$

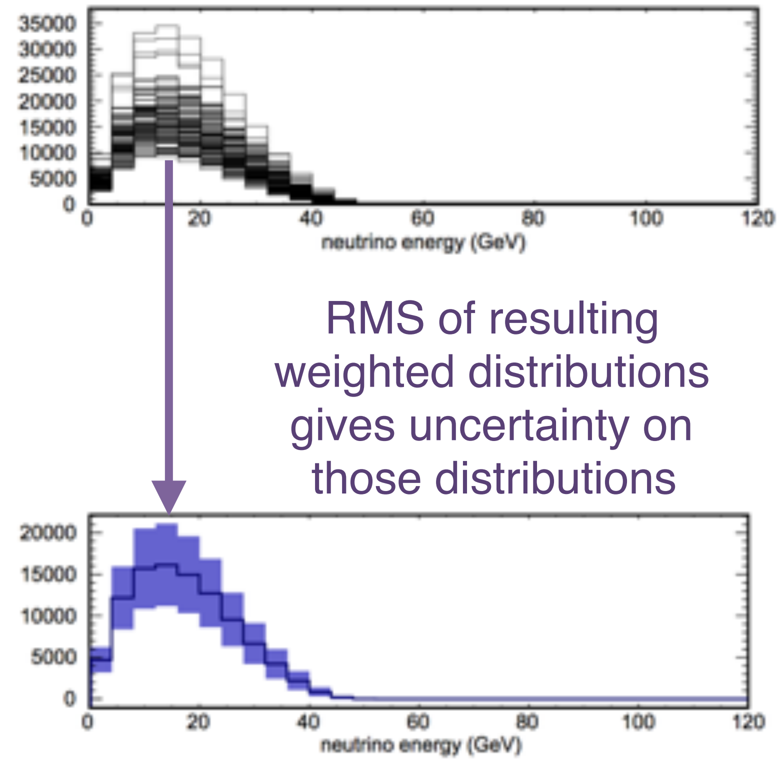


Weights for events with multiple interactions are the product of individual interaction weights

Constraining the NuMI Flux

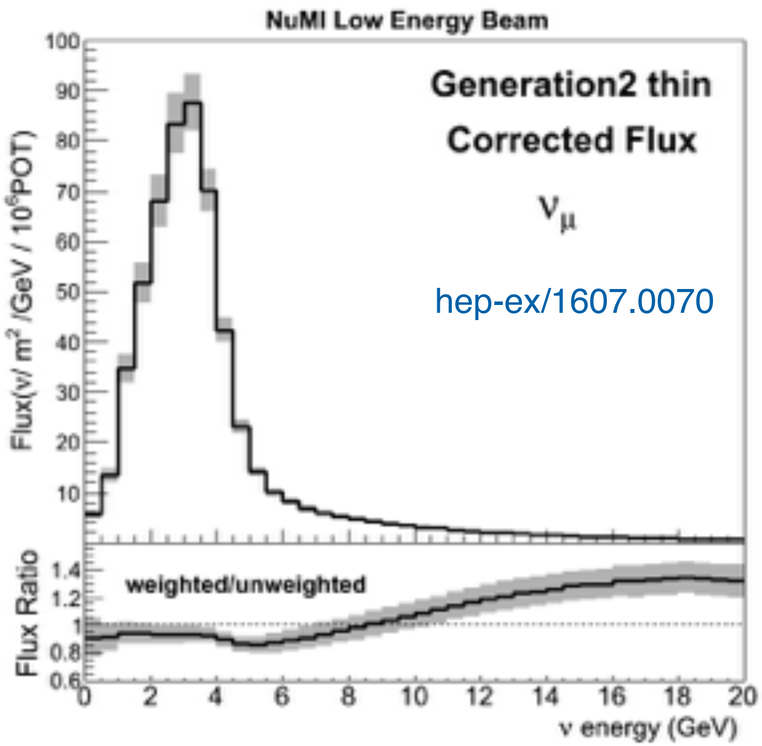
- Uncertainties on the external data constraints are propagated to uncertainties on our flux using the many universes method:

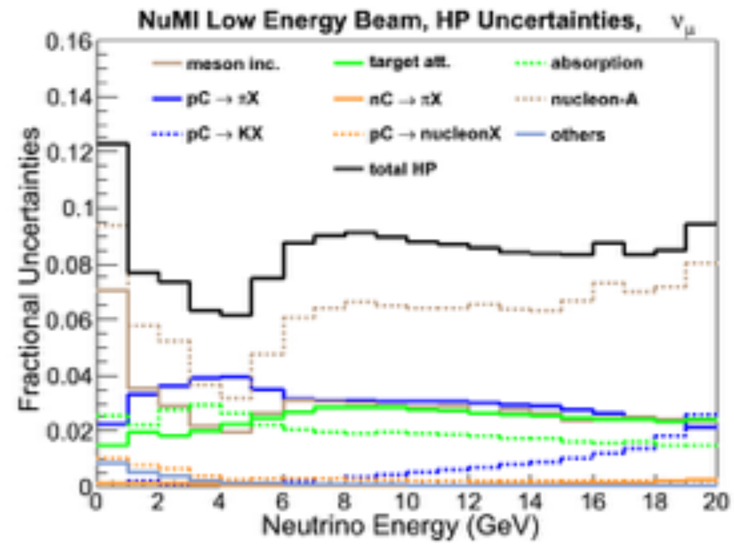
- For each event, in addition to the central value weights, we also store many (~1000) weights constructed from data cross sections varied according to their uncertainties (taking into account correlations)



Constraining the NuMI Flux

- The resulting flux / uncertainties:

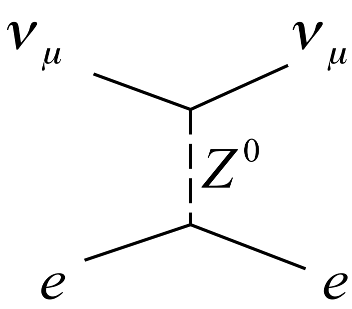




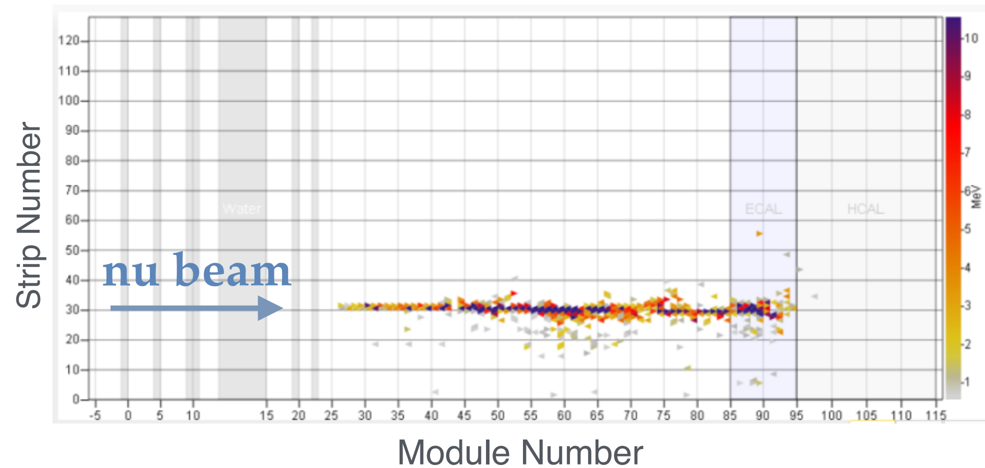
Constraining the NuMI Flux

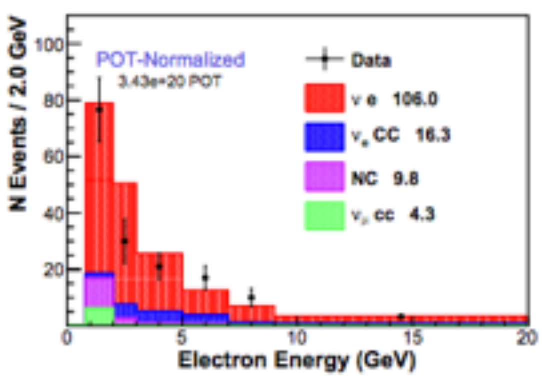
- Also pioneering use of a “new” standard candle for flux estimation: neutrino scattering on electrons:

$$\sigma = \frac{N}{\epsilon A \Phi}$$



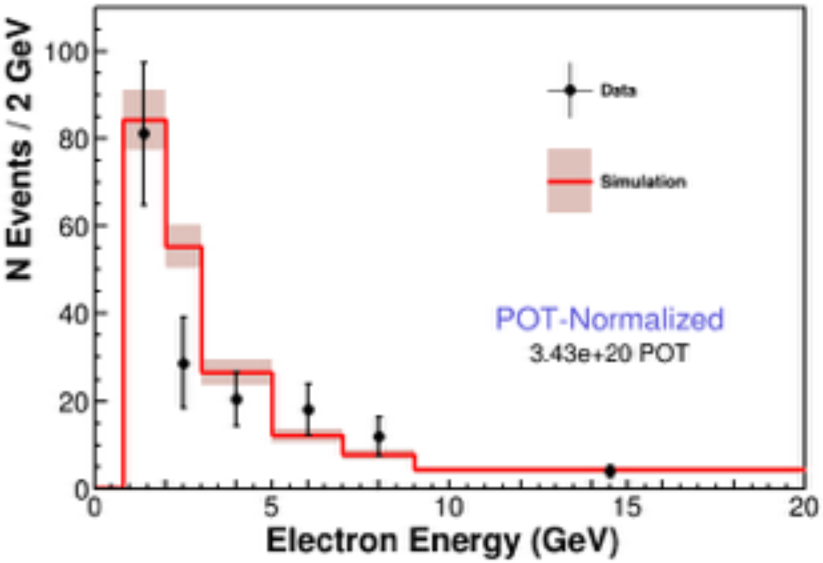
Phys. Rev. D 93, 112007 (2016)





- Well understood electroweak process
- Signal in MINERvA is a single electron moving in the beam direction
- Process cross section is smaller than nucleus scattering by a factor of 2000 -> statistically limited

Constraining the NuMI Flux



Phys. Rev. D 93, 112007 (2016)

Predicted number of signal events, given (an older version of) Geant4 simulation constrained with external data:
149 ± 19

Observed in Data:
135 ± 17.0

How to combine this with our existing flux model?

Constraining the NuMI Flux

We use a Bayesian argument:

Probability of a model given our measurement

Probability of our measurement given the model

$$P(M|N_{\nu e\to\nu e}) \propto \pi(M)P(N_{\nu e\to\nu e}|M).$$

Prior probability of the model

Constraining the NuMI Flux

We use a Bayesian argument:

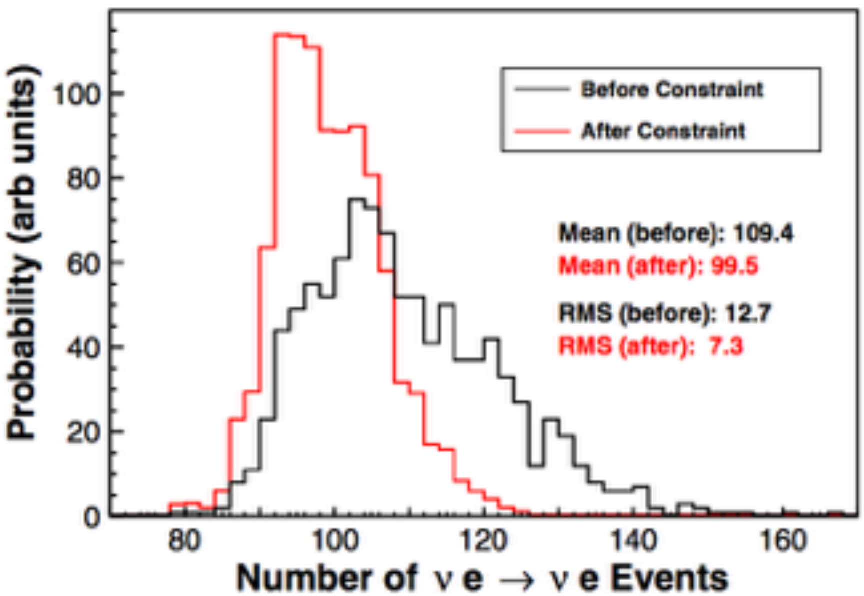
$$P(M|N_{\nu e\rightarrow\nu e}) \propto \pi(M)P(N_{\nu e\rightarrow\nu e}|M).$$

We estimate this by computing a chi-square between the measured electron energy distribution and the prediction for the universe in question

$$P(N_{\nu e\rightarrow\nu e}|M) = \frac{1}{(2\pi)^{K/2}}\frac{1}{|\Sigma_{\mathbf{N}}|^{1/2}}e^{-\frac{1}{2}(\mathbf{N}-\mathbf{M})^T\Sigma_{\mathbf{N}}^{-1}(\mathbf{N}-\mathbf{M})}$$

Constraining the NuMI Flux

An example using the total number of predicted neutrino-electron scattering events:



Each entry in the "before constraint" distribution corresponds to a "flux universe"

To produce "after constraint", each original entry is weighted by the probability of that universe given the neutrino-electron scattering measurement

$$P(N_{\nu e \to \nu e}|M) = \frac{1}{(2\pi)^{K/2}} \frac{1}{|\Sigma_{\mathbf{N}}|^{1/2}} e^{-\frac{1}{2}(\mathbf{N}-\mathbf{M})^T \Sigma_{\mathbf{N}}^{-1} (\mathbf{N}-\mathbf{M})}$$

Constraining the NuMI Flux

The same weights can be applied to constrain the flux uncertainty any quantity predicted by our simulation:

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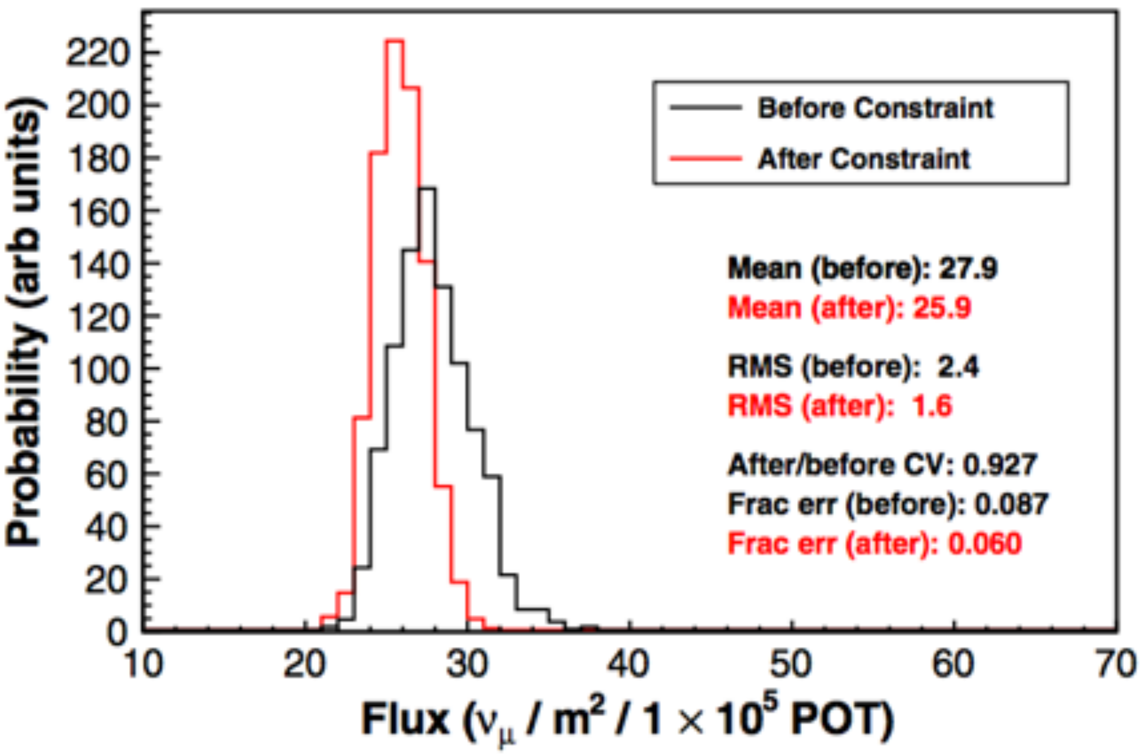
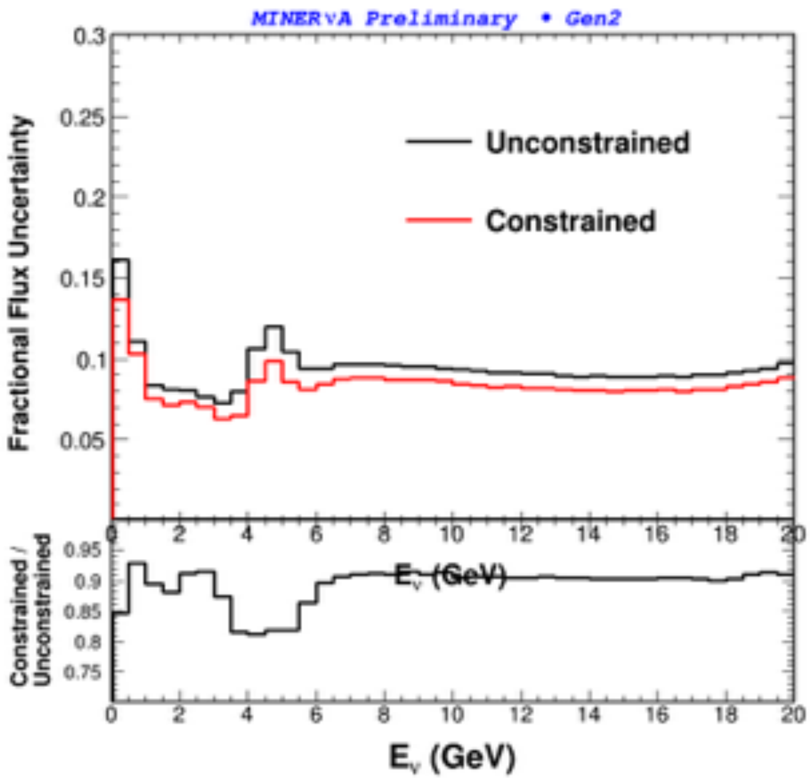
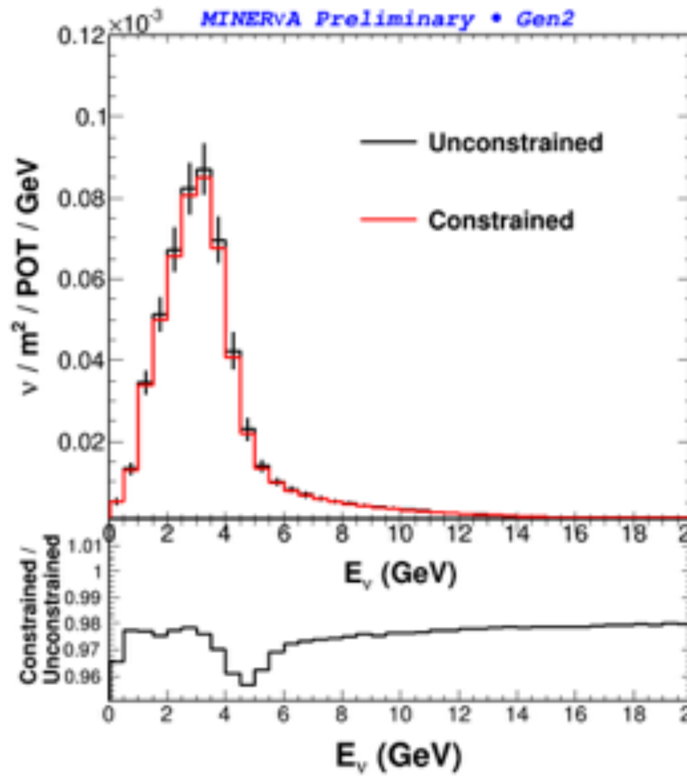


Probability distributions for total muon neutrino flux integrated between 0-10 GeV, before and after constraint

Constraining the NuMI Flux



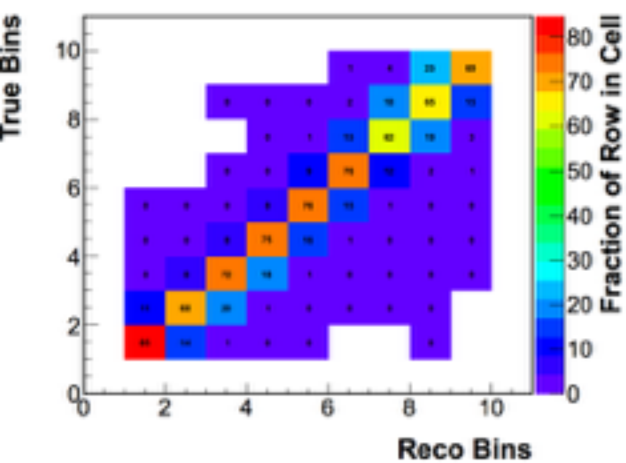


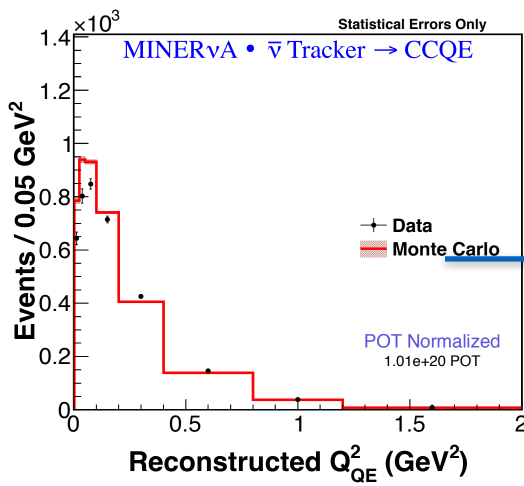
- This statistically limited result reduces MINERvA's flux uncertainties as a function of energy by 10-20% (of the a priori uncertainties)

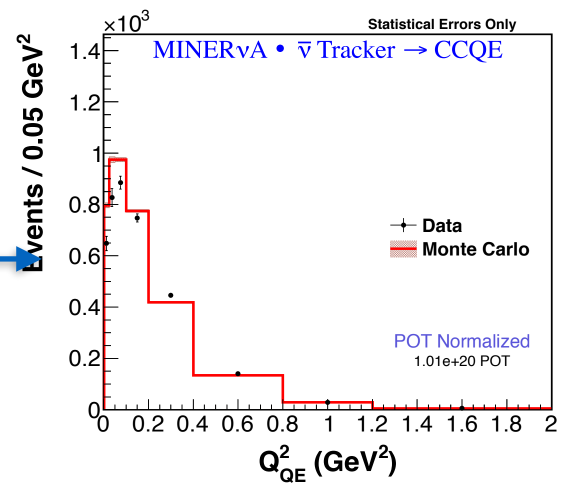
Unfolding

Unfolding

- I promised you I would say more about unfolding:



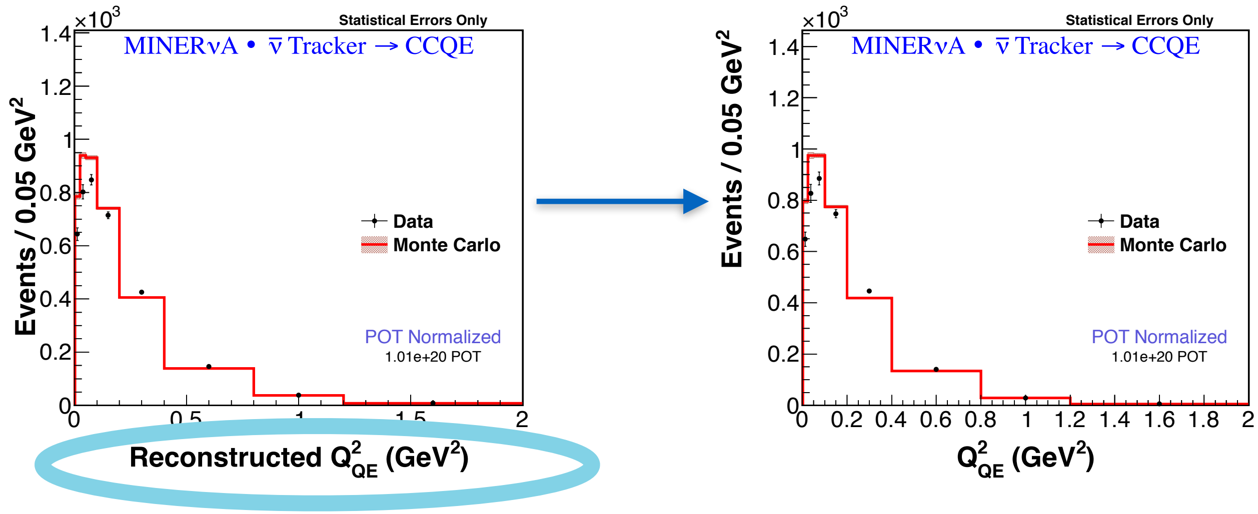




$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i\left(\Phi T\right)\Delta Q^2_{\mathrm{QE},i}}$$

Unfolding

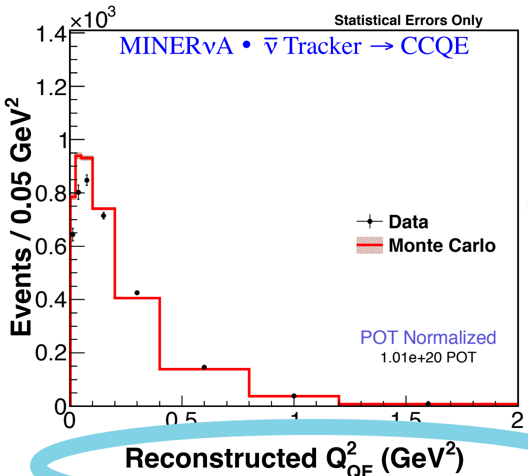
- We try hard to define analyses such that we are unfolding to correct for detector smearing and not for highly model-dependent effects such as final state interactions:

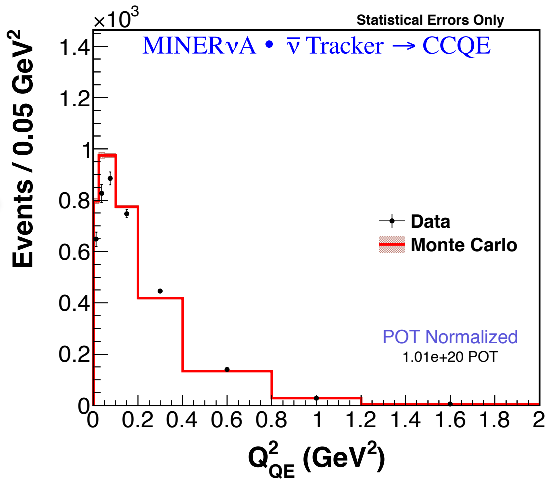


In principle, Q^2 is the 4-momentum transferred from the neutrino to the final state nucleon

Unfolding

- We try hard to define analyses such that we are unfolding to correct for detector smearing and not for highly model-dependent effects such as final state interactions:





In practice (for this analysis), we approximate Q^2 using measurements of the final state muon's energy and angle

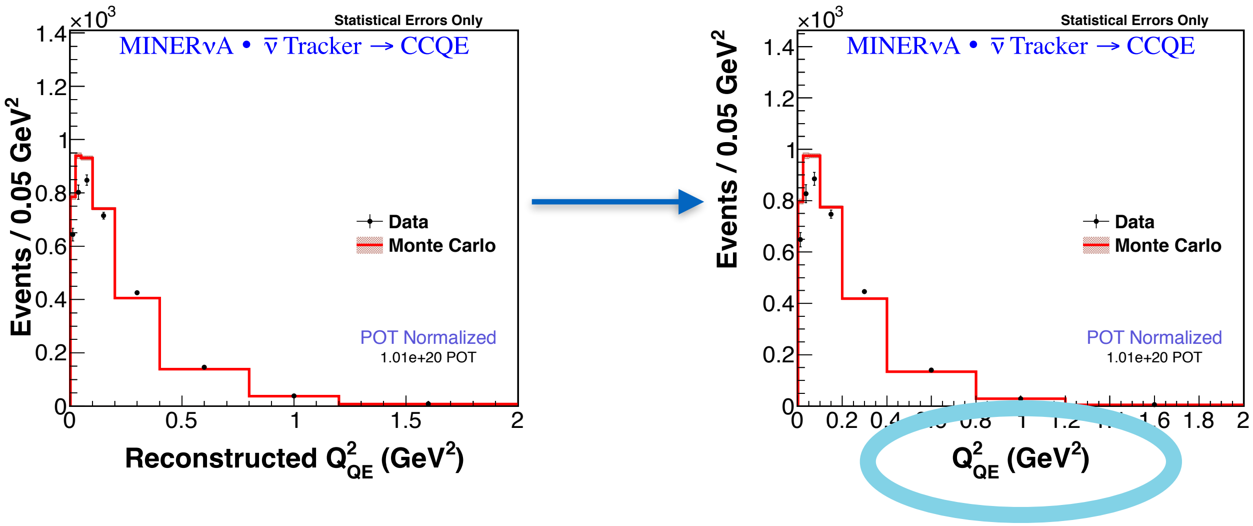
$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2,$$

Even if we could perfectly reconstruct the muon variables, this differs from the original interaction Q^2 due to initial state nucleus effects

Unfolding

- We try hard to define analyses such that we are unfolding to correct for detector smearing and not for highly model-dependent effects such as final state interactions:



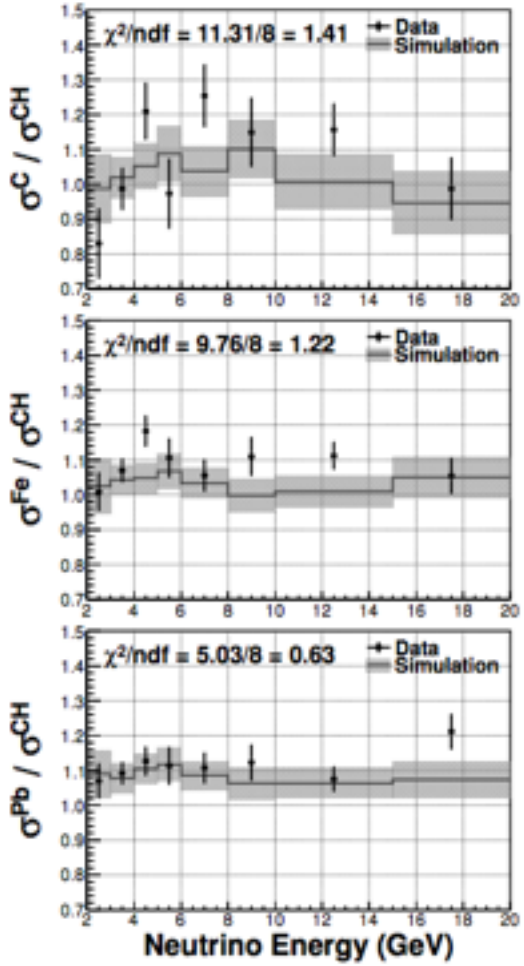
So we don't unfold to the original Q^2 of the nucleon interaction, but the same quantity we reconstruct, with reconstructed muon momenta replaced by true muon momentum leaving the nucleus

$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2,$$

Unfolding

- This is not always possible:



For our charged current inclusive measurements, we reconstruct neutrino energy by adding muon energy to calorimetricaly corrected recoil

We have to rely heavily on models to tell us the relationship between the recoil energy we see in the detector and the true recoil energy (e.g. the number of neutrons that leave the detector)

Unfolding

- We use iterative bayesian unfolding as implemented in RooUnfold

Bayesian Method

The Bayes' theorem is used repeatedly to get the best estimates of the true distribution [1]. Considering:

$$\hat{n}(C_i) = \sum_{j=1}^{n_E} M_{ij}\, n(E_j)$$

- $\hat{n}(C_i)$: Unfolded distribution.
- M_{ij} : Unfolding Matrix
- $n(E_j)$: Folded distribution

The Bayesian method is used for calculating the unfolding matrix:

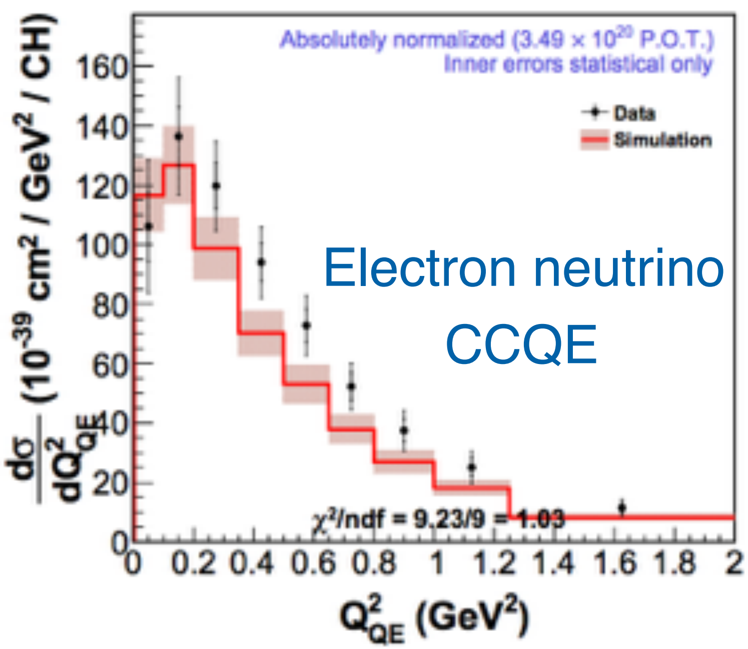
$$M_{ij} = \frac{P(E_j|C_i)\, n_0(C_i)}{\epsilon_i f_j}$$

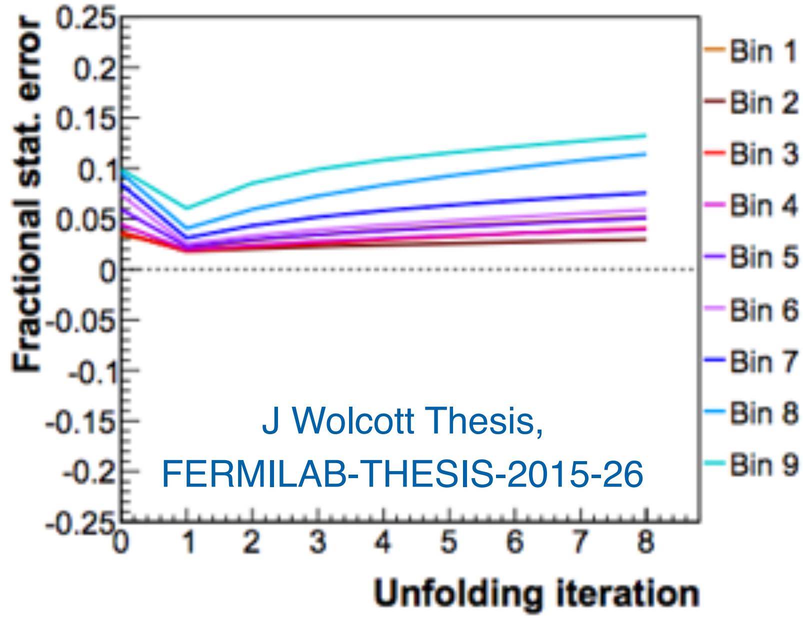
- $P(E_j|C_i)$: Migration Matrix
- ϵ_i : Efficiencies
- f_j : folded prior distribution
- $n_0(C_i)$: arbitrary, then updated from previous $\hat{n}(C_i)$ it.

[1]A multidimensional unfolding method based on Bayes' theorem, G.D' Agostini, NIM-A Vol. 362, No. 2-3. (15 August 1995)

Unfolding

- The big question for every analysis: how many iterations?
  - More iterations give you less model dependence but higher statistical uncertainties

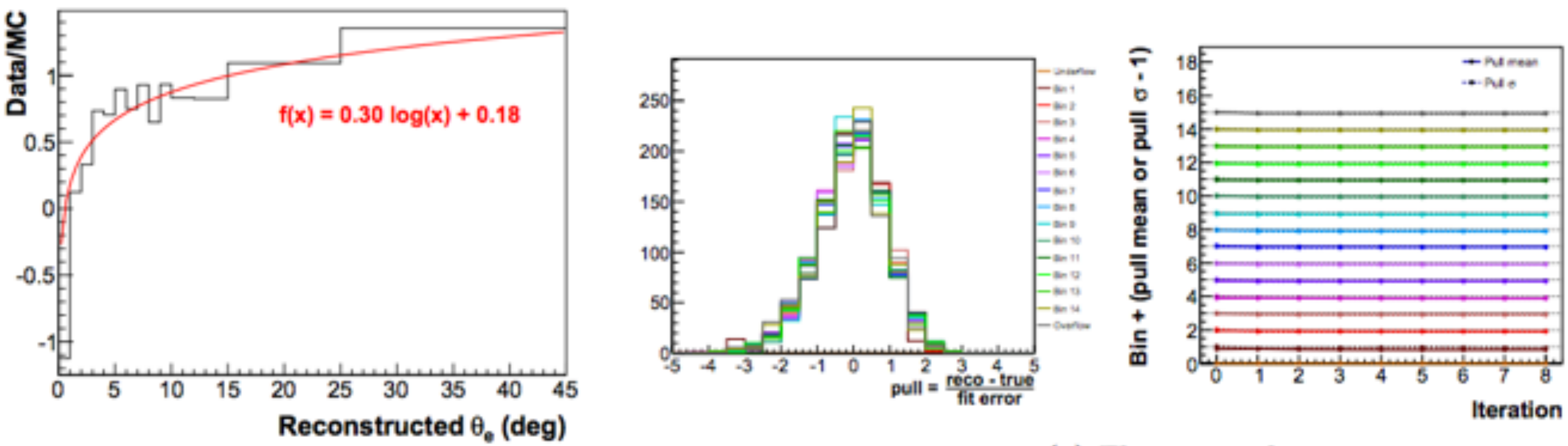




Fermilab

Unfolding

- The big question for every analysis: how many iterations?
    - Each analyzer does a study where they warp the underlying MC distribution and study how many iterations are required to ‘recover’ the original MC distribution

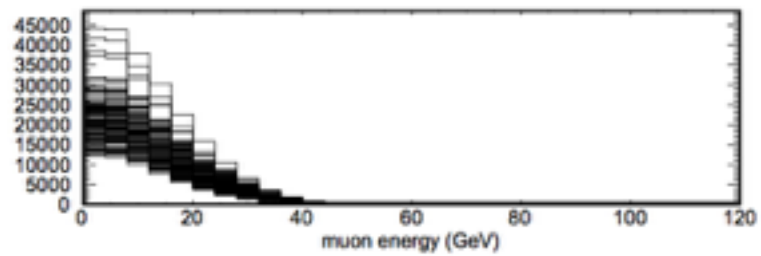


(a) Electron angle

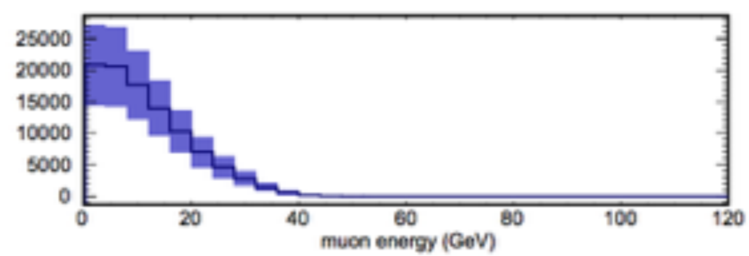
Unfolding Systematic Uncertainties

- Systematic uncertainties due to model dependence of the unfolding is assessed by performing unfolding in all of the varied systematic universes

In principle, you'd want to vary the unfolding matrix for all systematics variation

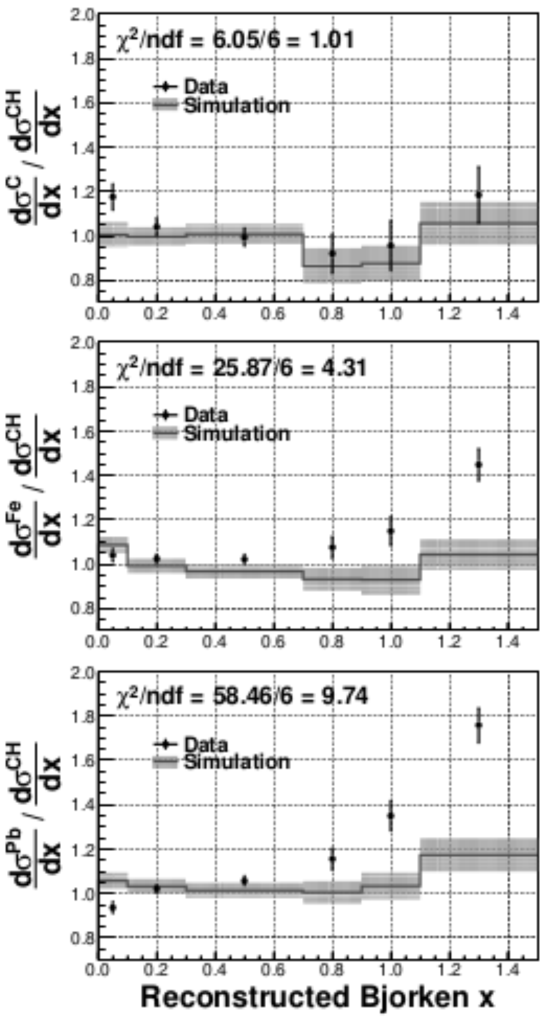


In practice, we find this inflates systematic uncertainties with statistical fluctuations; we generally only vary the unfolding matrix in cases where we expect the variation to impact the matrix



Unfolding

- And in some cases we don't unsmear at all:



Phys. Rev. Lett. 112, 231801

For example, charge current inclusive ratios across nuclear targets as a function of x, which has large amounts of smearing

$$x = \frac{Q^2}{2M\nu}$$

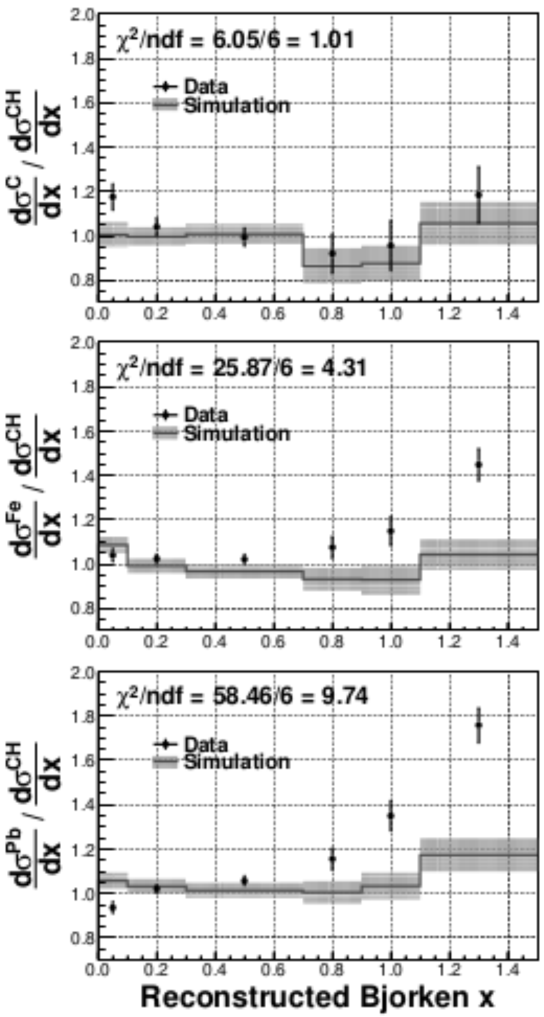
high x = more elastic

$$\nu = E_\nu - E_\mu$$

$$Q^2 = 2E_\nu \left(E_\mu - p_\mu cos\left(\theta_\mu\right)\right)$$

Unfolding

- And in some cases we don't unsmear at all:



Phys. Rev. Lett. 112, 231801

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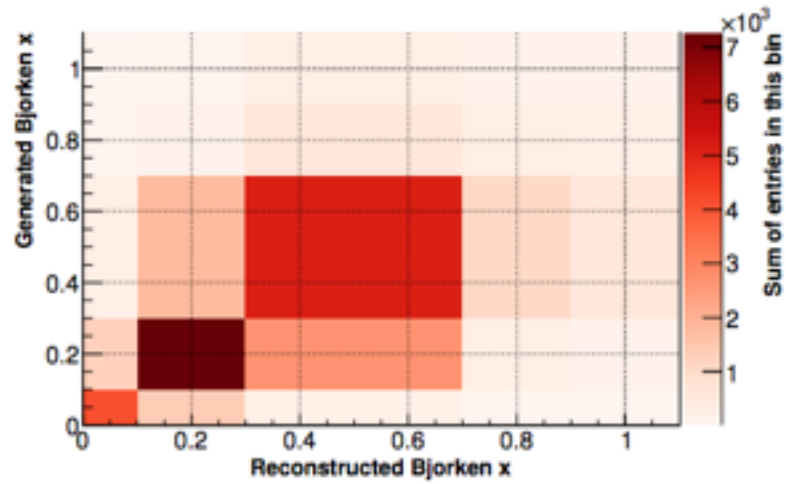


(b) x_{bj}, Lead of Target 4

Conclusion

- MINERvA has lots of data
- With it comes a lot of statistical challenges
- We try to do a good job of meeting them, in spite of none of us being statisticians
- In some cases (e.g. flux constraint), we are developing techniques that are likely to be useful to future oscillation experiments
- Your comments are welcome!

From the MINERvA Collaboration:

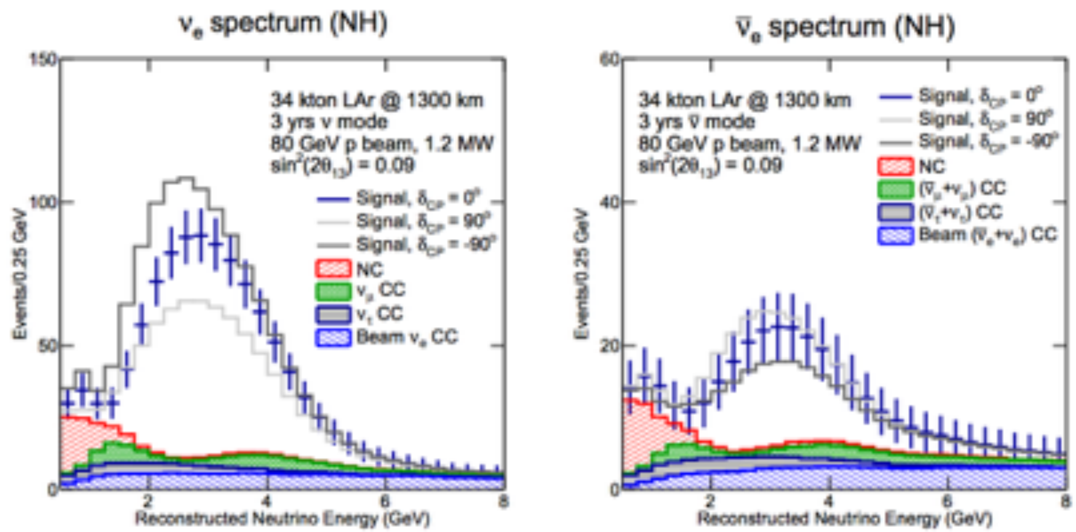
Thank You!!

Searching for Rare Processes: Coherent Kaon Production

Introduction: Why

- MINERvA makes measurements that support long-baseline experiments such as DUNE

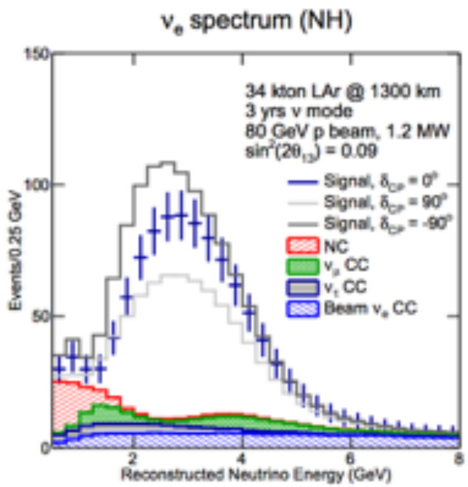
Expected ν_e and $\bar{\nu}_e$ energy spectra that will be observed at DUNE, for different values of the δ_{CP}

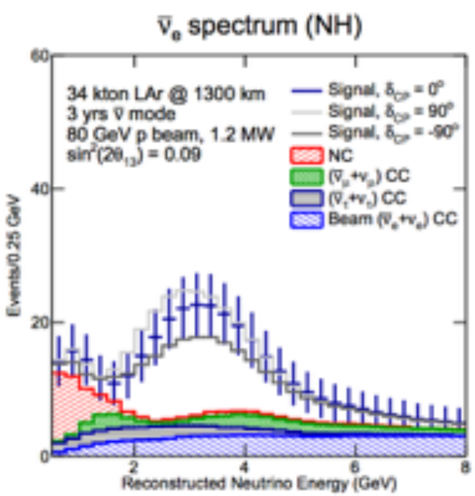


LBNE arXiv:1307.7335

- DUNE will make many of its measurement by comparing what they see with predictions

Introduction: Why

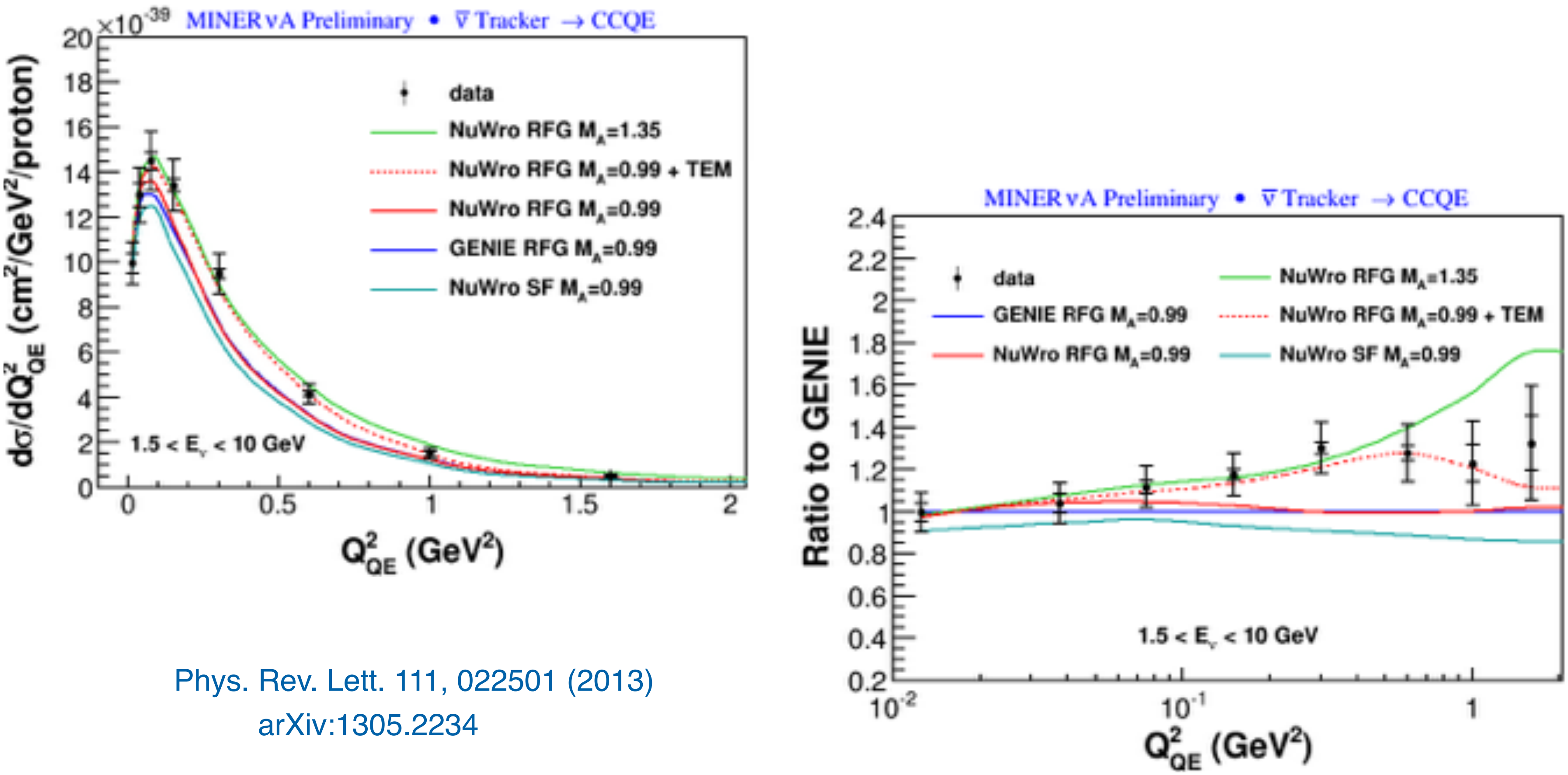




- To produce these predictions, we need a detailed model of neutrino interactions with matter
  - **list of all the types of neutrino interaction** processes that can occur in the detector
  - The **probability** that each process will happen (which we call the **cross-section**)
  - **What they look like** when they do
- This is one of the biggest source of systematic uncertainty for experiments like DUNE

Introduction: How

- We typically compare our final cross sections to models, and make the data available to future model tuners:

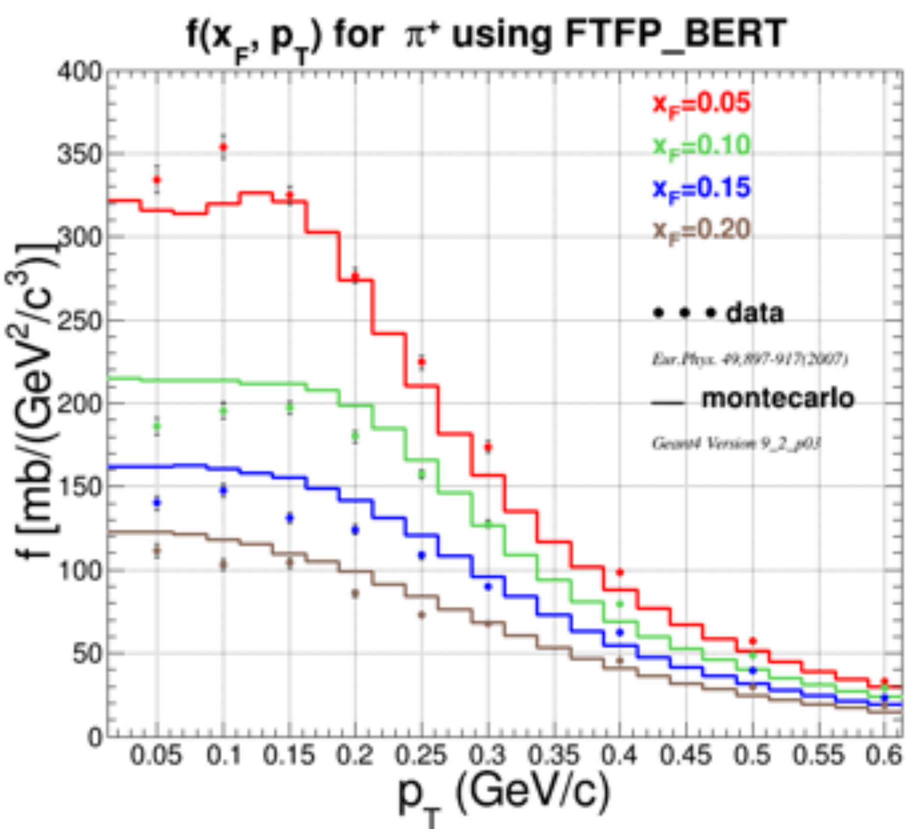


Phys. Rev. Lett. 111, 022501 (2013)
arXiv:1305.2234

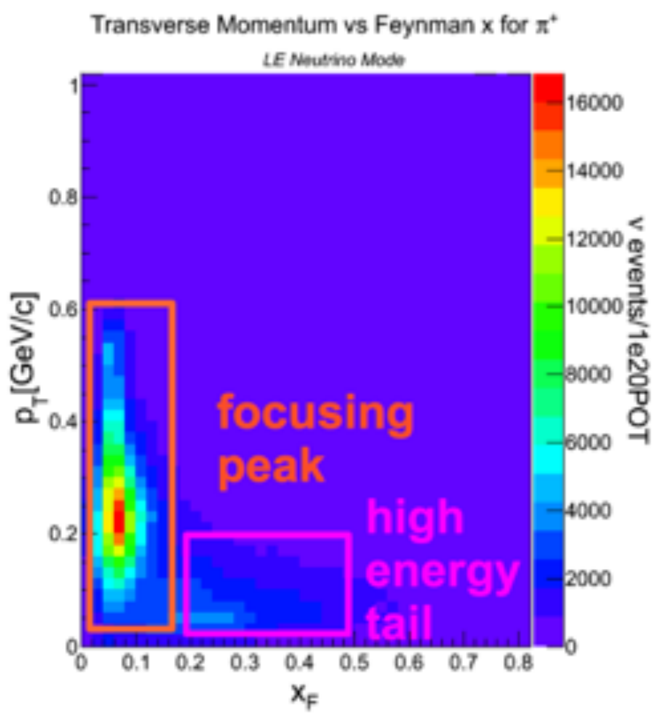
Constraining the NuMI Flux

- One problem: Geant4 does not always agree with external data:

$f(x_F, p_T) = E\, d^3\sigma/dp^3$ = invariant production cross-section

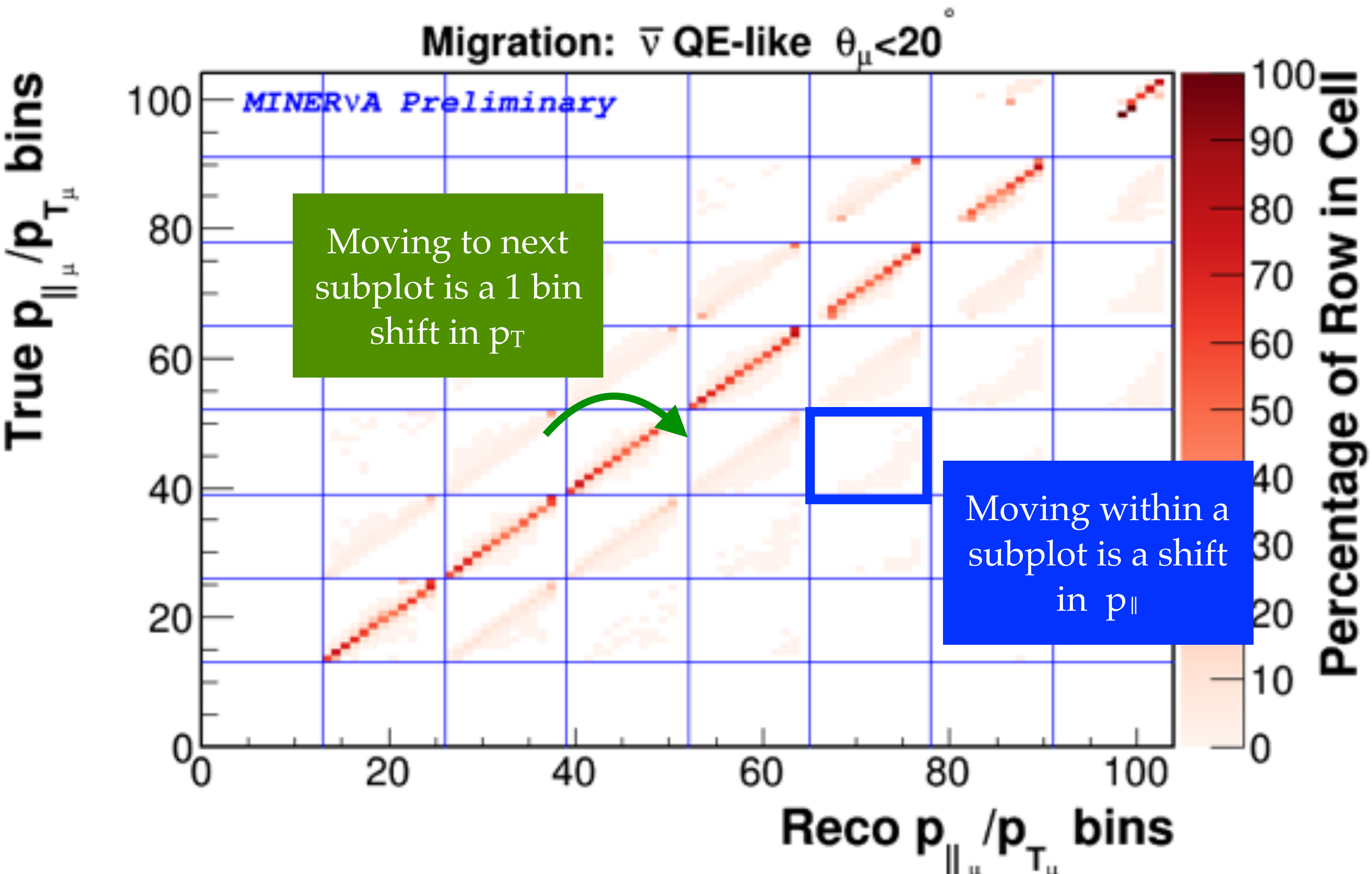


$$x_F = 2\frac{P_L}{E_{cm}}$$



Unfolding

- Unfolding becomes and even greater challenge for analyses measuring two dimensional cross sections:



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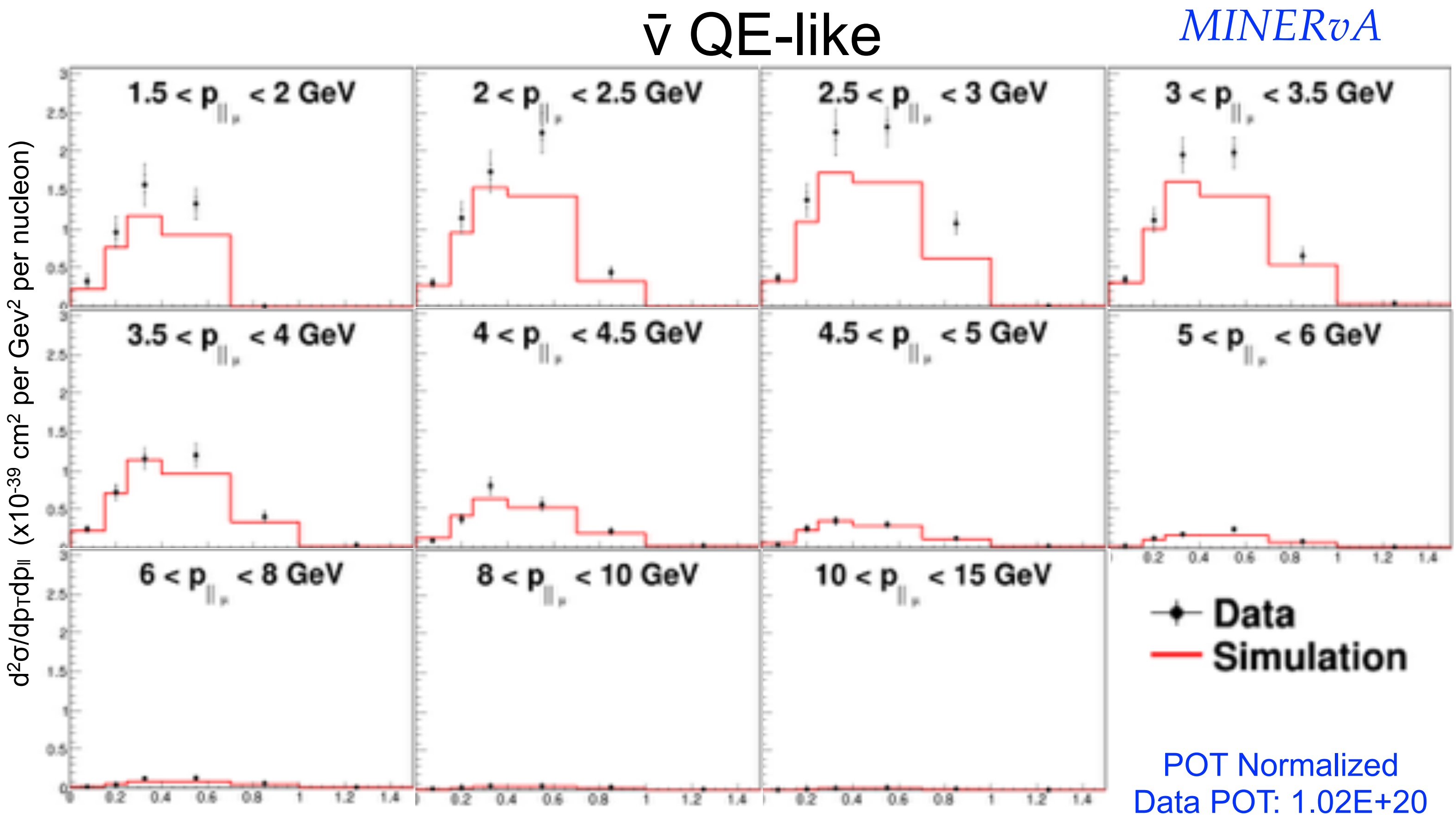
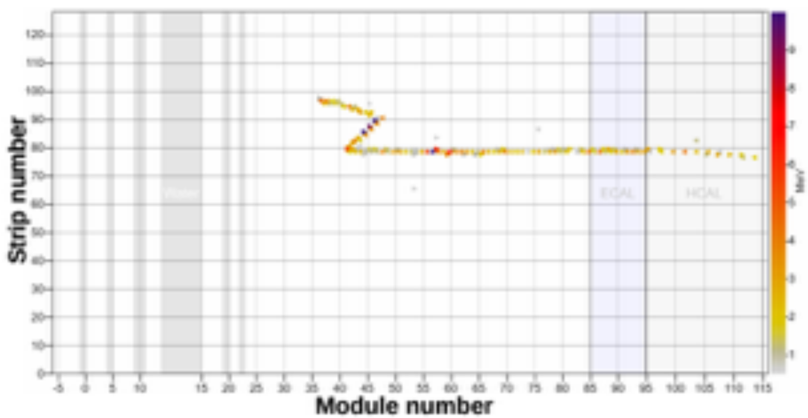


FERMILAB-THESIS-2015-26

Kaon Production

- Kaon production by neutrinos is interesting because it is a background to proton decay measurements
- One potential source of kaon production is coherent kaon production
  - Veeery small cross section — never seen before
  - But MINERvA went looking for it



(a)

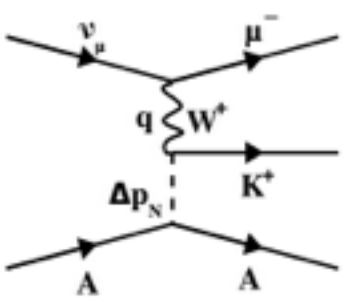
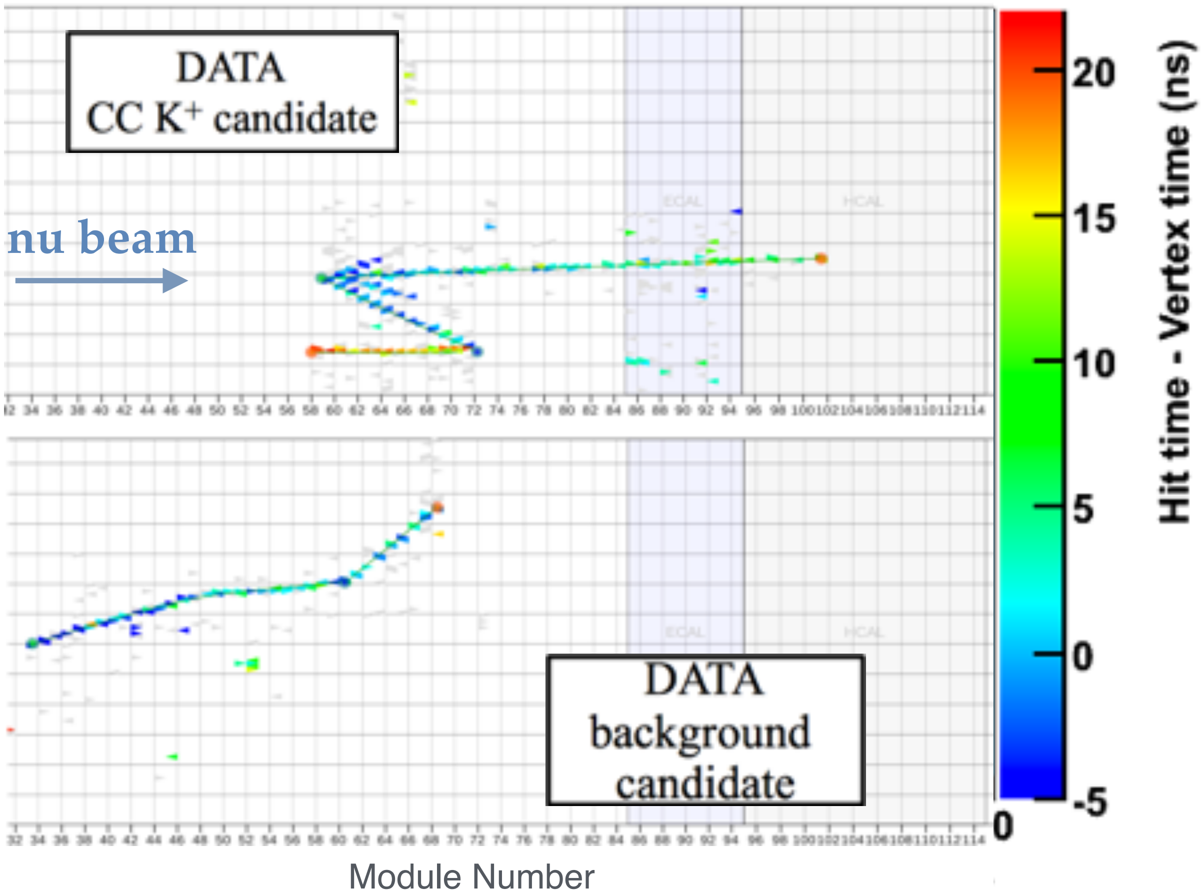


FIG. 1: Feynman diagram for coherent charged kaon production. The square of the momentum transfer to the nucleus is $|\Delta p_N|^2 = |q - p_K|^2 = |t|$.

Phys. Rev. Lett. 117, 061802 (2016)

Kaon Production



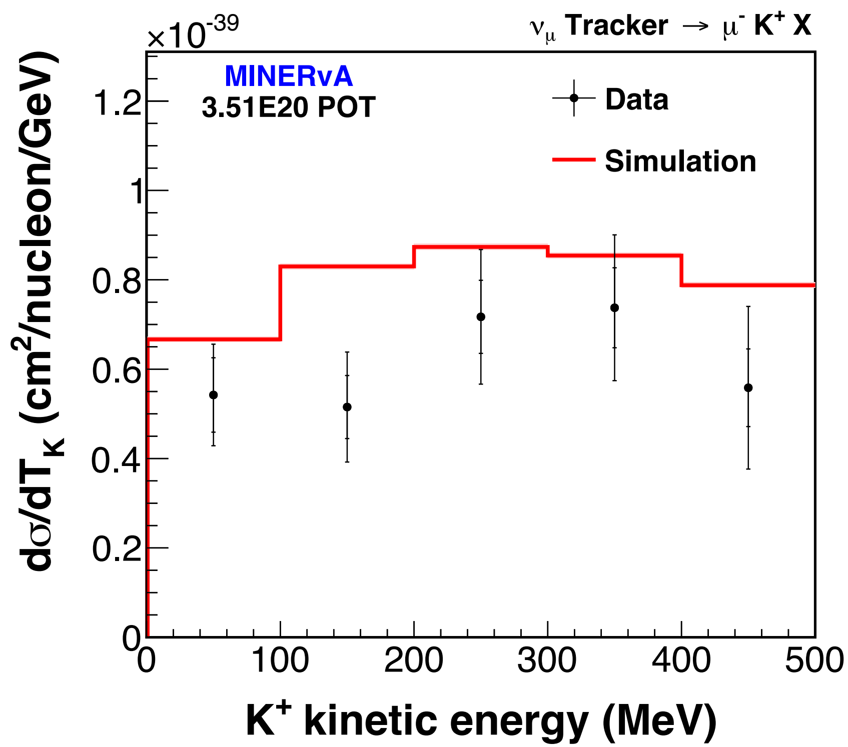
Key distinguishing feature of kaons for MINERvA: time separation of kaon and decay products

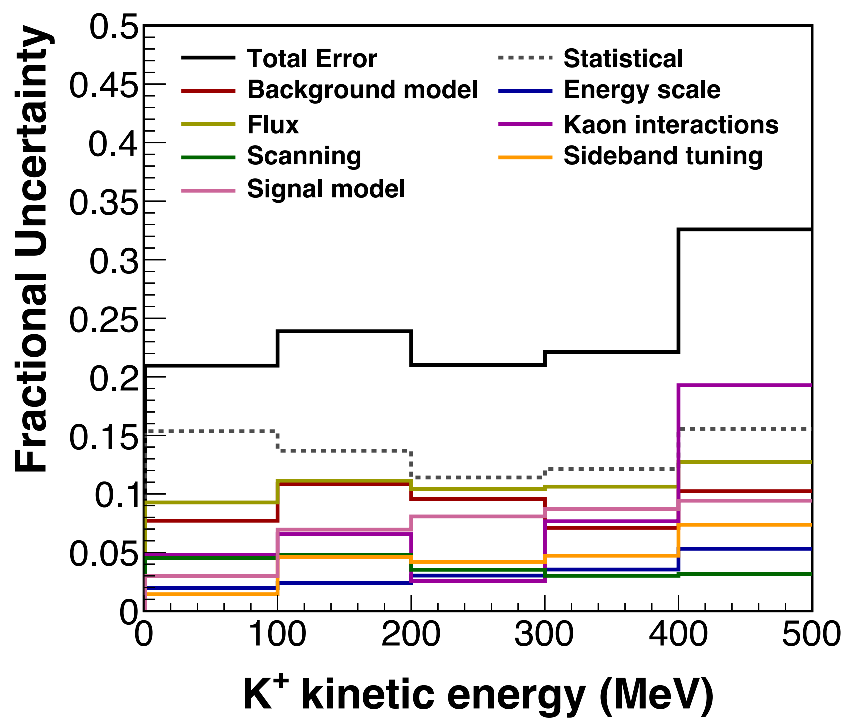
Here, color denotes hit time

Kaon Production

- Charged current K+ production cross section shows reasonably good agreement with simulation.
- This measurement increased the world's sample of K+ production events from neutrinos from dozens to thousands!

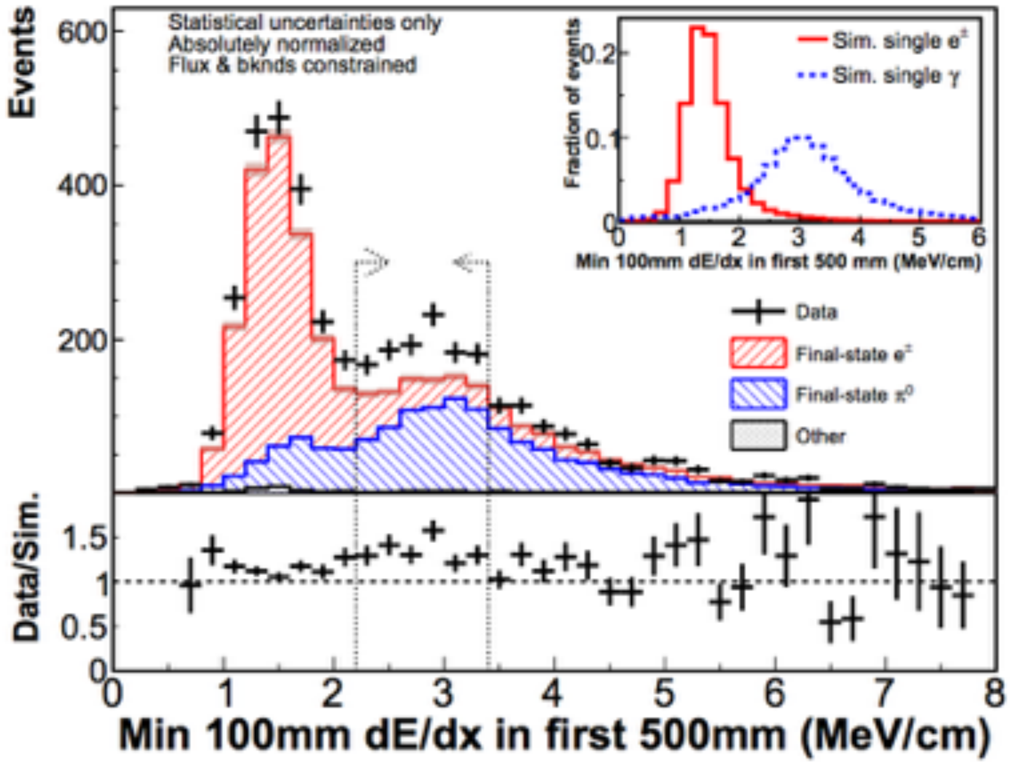
https://arxiv.org/abs/1604.03920





Neutral Current Diffractive Pion Production

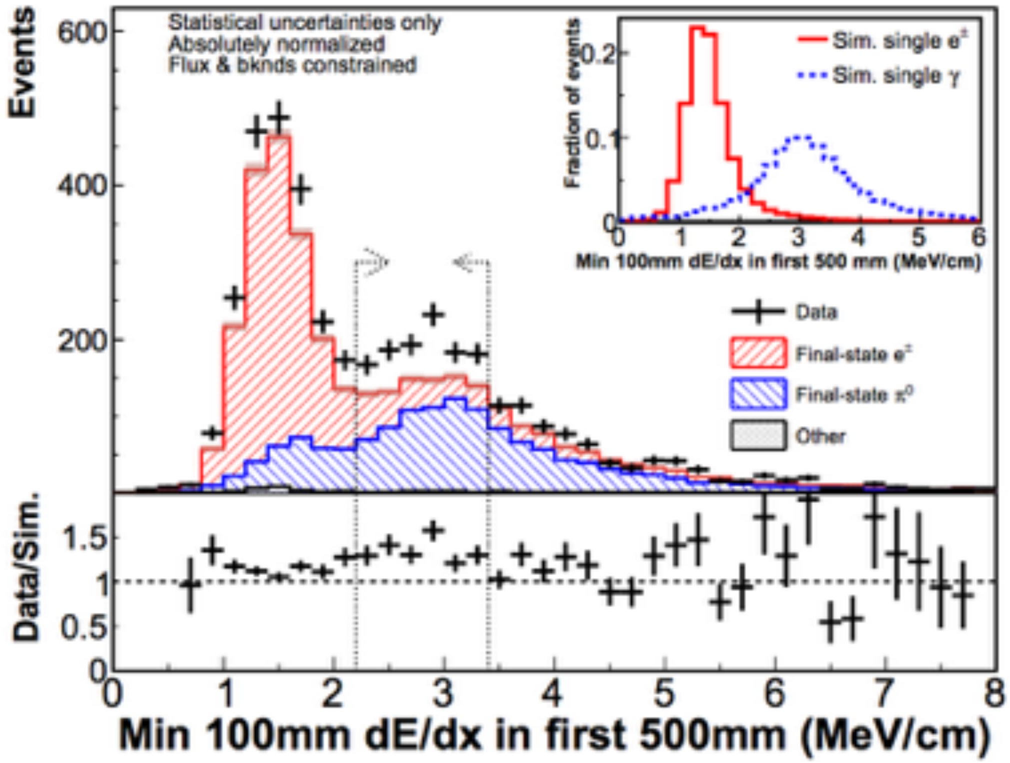
arXiv:1604.01728,
Phys. Rev. Lett. 116, 081802 (2016)



Sometimes when we go hunting for the golfballs of oscillation experiments…

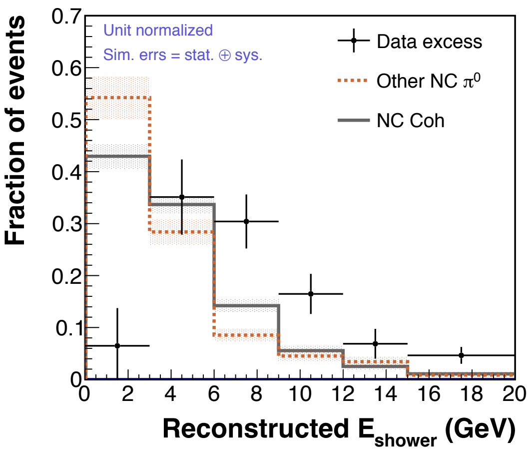
Neutral Current Diffractive Pion Production

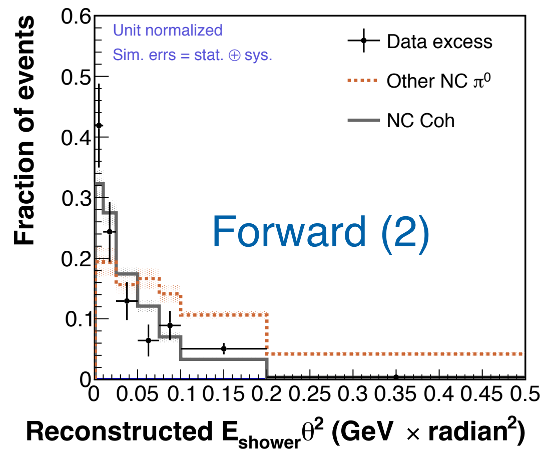
arXiv:1604.01728,
Phys. Rev. Lett. 116, 081802 (2016)



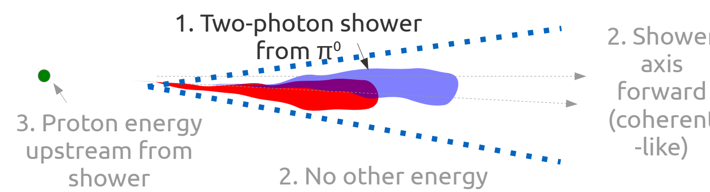
… we also find alligators!

Neutral Current Diffractive Pion Production





1) Two-photon Shower
2) Coherent-like scattering
   - Forward Kinematics
   - Very little other energy
3) Visible proton energy



arXiv:1604.01728

NC diffractive π^0 production from Hydrogen